



Multidecadal assessment of environmental variables in the river Ganga for pollution monitoring and sustainable management

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Abstract The Ganga River is the major source of drinking water for humans over the decades. It is also the ecological niche for millions of relict species, i.e., for a variety of planktons, benthic organisms, fish, and various other aquatic organisms. The blasting population resulted in an enhanced rate of pollution in the river system emanating from various anthropogenic activities and industrialization in the bank of river Ganga. The study was made in the middle and lower stretch of the river to monitor the decadal changes in the water quality of river Ganga from 1960 to 2019 at six different study sites. In the present study, various water quality parameters such as dissolved oxygen, pH, free carbon dioxide, total alkalinity, conductivity, total dissolved solids (TDS), hardness, chloride, and nitrate have been studied during 2015–2019. The data for 1960 to 2006 were taken from ICAR-CIFRI publications. Based on the studied parameters, National Sanitation Foundation (NSF)—water quality index (WQI) was calculated. In the present study, it was found that the calculated NSF-WQI was 69.24 in 1960–1961 which increased up to 113.39 during 2001–2006. But, with the implementation of various rejuvenating strategies, the WQI of the river got reduced to 106.48 during 2015–2019.

This reflected the positive changes in the riverine system. Different water quality parameters such as dissolved oxygen, pH, and hardness were observed mostly within the permissible range as based on the drinking water guidelines for humans and survival of the aquatic organisms as well, except a few location-specific observations.

Keywords River Ganga · Multi-decadal · WQI · Ecological niche · Anthropogenic

Introduction

River Ganga is the fifth largest river system in the world and the largest in India flowing a distance of 2525 km and covers 8,61,404 km² basin area which is 26.3% of the country's total landmass (Trivedi, 2010). It is a substantial source of livelihood for more than 530 million people (Tare et al., 2013). Due to the multifaceted use of river water in diverse sectors like domestic household use, drinking water, irrigation, transport, tourism, and fisheries, the river is considered as the lifeline for a sheer number of people living within and around the catchment area. (Samanta, 2013). River Ganga is also an ecological niche for many relict organisms including plankton species, benthic organisms, and fish, which are key organisms of the aquatic ecosystem (Sinha, 2015). The blasting population has resulted in a multifold rise in industrialization (Goel, 2006) which often discharges untreated wastes in the river. The construction of dams,

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barrages, embankments, hydroelectric projects, etc. has emanated multiple challenges on the ecological integrity of the river (Singh et al., 2019). The water quality status of the river has regularly been monitored by several researchers from various organizations for many decades and has indicated noteworthy changes over the years. Significant differences in water quality were reported in different stretches of the river with severe deterioration in some stretches depending upon the gravity of anthropogenic influences (Mohanty et al., 2022). As river Ganga is considered a sacred river, various initiatives including the Ganga Action Plan (GAP) were in place to restore the previous status of the riverine water quality. The present communication aims to compare the multi-decadal changes in the water quality status of the river system by the use of various univariate as well as multivariate statistical tools like principal component analysis, discriminant analysis, two-way ANOVA, and cluster analysis; as used by many researchers for the zonation of the river systems (Azhar et al., 2015; Gyimah et al., 2021; Jung et al., 2016; Njuguna et al., 2020). The water quality index is a single unitless number that describes the quality of the water as derived from the mathematical expressions utilizing some selected critical groundwater quality parameters such as dissolved oxygen, pH, free carbon dioxide, total alkalinity, conductivity, TDS, hardness, chloride, and nitrate. The requirement of the WQI is well known as it is not possible to evaluate the quality of the water by using multiple parameters individually (Chapman, 1996), and thus, many of the researchers use the WQI for the comprehensive assessment of the riverine water quality (Iqbal et al., 2019). The water quality index has been widely adopted using a varied number of water quality parameters (Bhargava, 1983; Chauhan & Singh, 2010; Cude, 2001; Matta, 2014). There are multiple numbers of WQI's available for the classification of the aquatic system but none of them are universally accepted (Kumar et al., 2021). The various commonly used WQI methods are CCME-WQI, I-WQI, Bhargava-WQI, and NSF-WQI (Lumb et al., 2011). But among all these, the water quality index developed by the U.S. National Sanitation Foundation, i.e., NSF-WQI is a widely accepted WQI method in Asia and all across the rest of the globe (Deshmukh & Aher, 2016; Noori et al., 2019). In the Ganga River system also, the NSF-WQI has been predominantly used by many researchers to classify the riverine water

quality (Ansari & Kumar, 2022; Johnstone et al., 2022). A majority of the researchers have used the NSF-WQI for the classification of the river system so, in the present study also the NSF-WQI has been used to illustrate multi-decadal changes in overall water quality status at selected stations in the middle and lower stretches of the river Ganga from 1960 to 2019. Along with NSF-WQI, changes of major individual water quality parameters responsible for the monitoring of riverine health have also been discussed.

Materials and methods

The study has been depicted in 5 important subparts comprising of the selection of the study area, sample collection, sample analysis, data curation, data analysis, and result (Fig. 1).

Study area

The study area comprised of six sampling stations located in the middle and lower part of river Ganga covering three important States of India, i.e., Uttar Pradesh, Bihar, and West Bengal situated at the freshwater zone of the river (Fig. 2), for which the GPS coordinates are presented in Table 1. All the study sites viz. Kanpur, Prayagraj, Varanasi, Patna, Bhagalpur, and Farakka are located in the bank of major cities and towns which have been established from time immemorial with the ever-increasing area and human population. The different study sites are having specified pollution sources that have affected the riverine water quality over the decades. Kanpur and Prayagraj is the most populous region located on the bank of river Ganga. The major pollution sources in the region are large paper industries, tanneries, distilleries, slaughterhouses, chemical factories, textile mills, and many small-scale industries. The study site Varanasi is affected by a large population load and various religious activities coupled with many small-scale industries in the region. Patna and Bhagalpur are the densely populated regions located in the state of Bihar. The major pollution sources in the region are religious activities, agricultural runoff, domestic discharge, and discharge from various small-scale industries. The study site Farakka is having a barrage, constructed in 1961. At Farakka, major pollution sources are

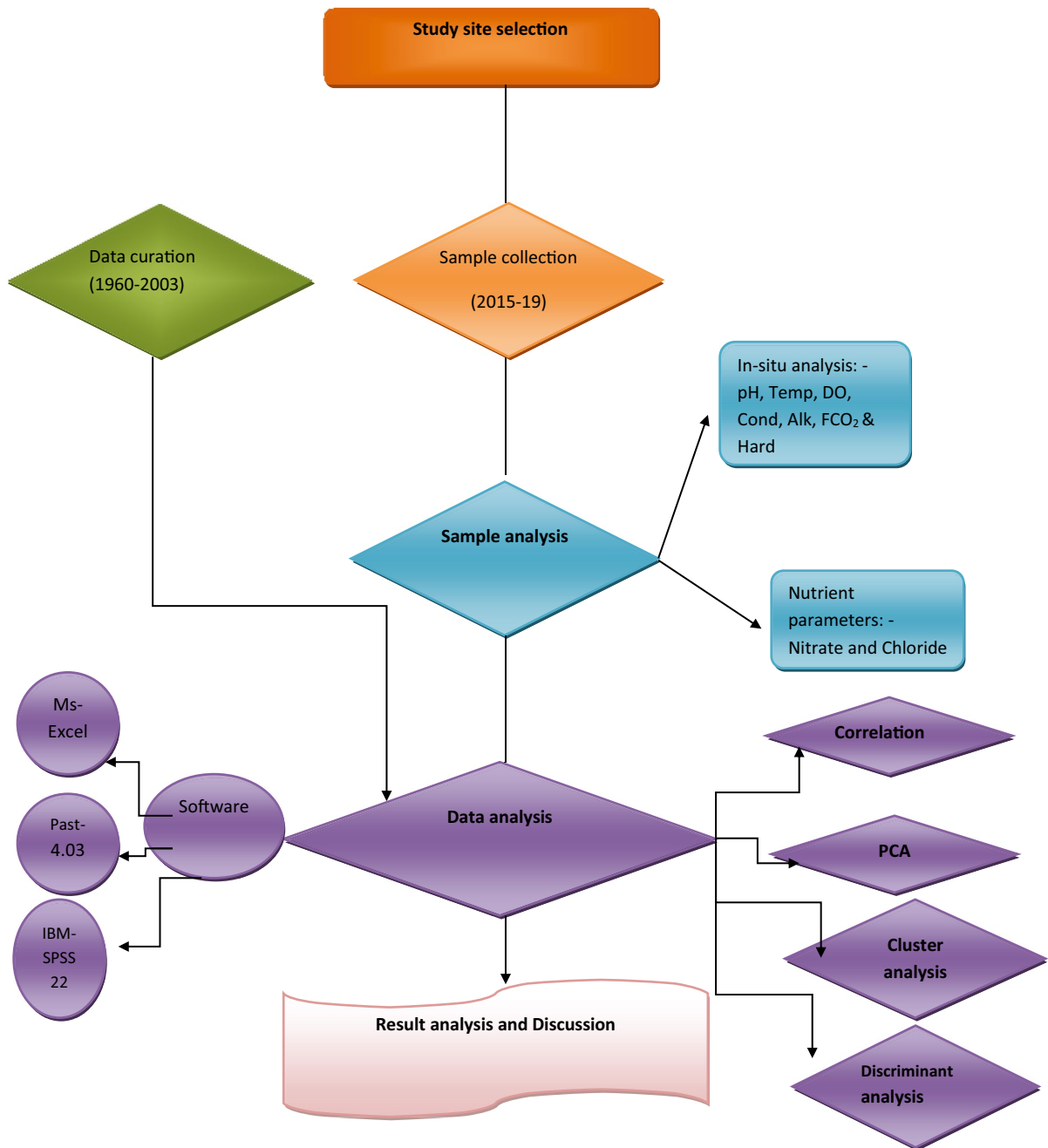


Fig. 1 Methodological flowchart used in the study process

agricultural runoff and various religious activities. The study area is having a humid subtropical wet climate but during the summer months of April to June; it is having a dry climate. Monsoon is from July to September when significantly higher riverine discharge is

observed. Post-monsoon covers the month of October to December whereas January to March may be considered as winter. The riverine resources are used for multiple purposes such as drinking, irrigation, fishing, transportation, and tourism.

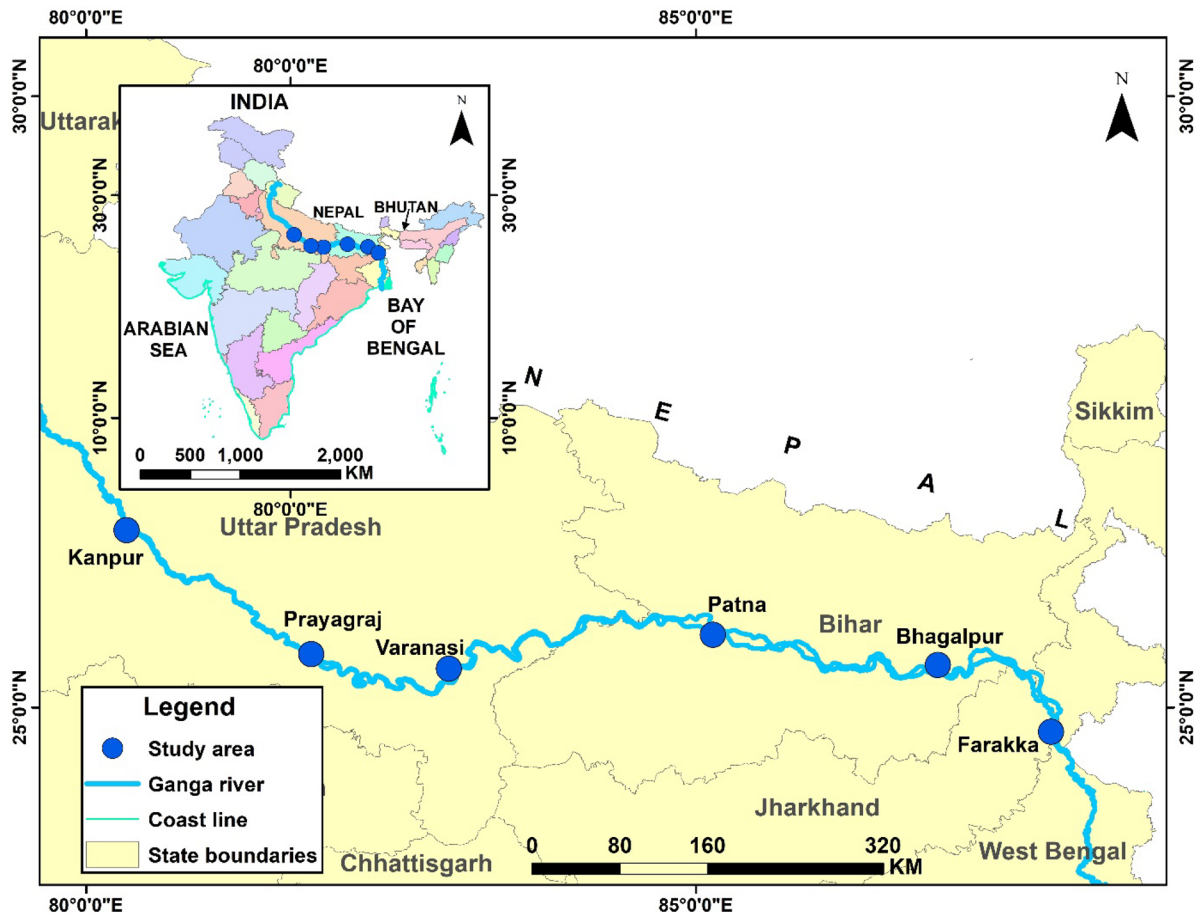


Fig. 2 Study area map of the sampling sites

Data acquisition

The study is based on the present study work conducted between 2015 and 2019 and data for past decades, i.e., from 1960 to 2006 have been collected from the bibliographic sources, i.e., from Bulletin No. 154 of ICAR-CIFRI Barrackpore (Vass et al., 2008).

Data from existing reports

For the study, previous water quality data have been collected from different bibliographic sources collected from Bulletin No. 154 of ICAR-CIFRI Barrackpore (Vass et al., 2008), which have been carried out at the same study sites as those of the present study sites. In

Table 1 GPS coordinates and major pollution sources of the studied sites

Sampling site	GPS co-ordinates	Major pollution source	Elevation
Kanpur	80° 33.18 N; 26° 44.99 E	Tanneries, chemical industries, color factories and agricultural runoff	126 m
Pryagraj	81° 84.63 N; 25° 43.58 E	Religious activities, Industries and agricultural runoff	98 m
Varanasi	82° 97.39 N; 25° 31.76 E	Religious activities, industries and agricultural runoff	80.71 m
Patna	25° 36.54 N; 85° 12.09 E	Religious activities, industries and agricultural runoff	55 m
Bhagalpur	25° 16.40 N; 87° 01.39 E	Religious activities, industries and agricultural runoff	52 m
Farakka	24° 08.13 N; 87° 09.18 E	Religious activities and agricultural runoff	30 m

the report, it is described that sampling was carried out and data were collected in four different seasons, i.e., winter, summer, pre-monsoon, and monsoon.

Water sampling and field measurement

For the present study, the sampling and analysis of the water samples were carried out from 2015 to 2019. The water samples were collected between 9 and 10 \Hrs in triplicates, preserved in prewashed Tarsons® HDPE bottles. Before each sampling, the bottles were rinsed with the river water. The sampling pattern was similar to the studies described in the bulletin of ICAR-CIFRI. The sampling was carried out in four major seasons, i.e., summer, monsoon, winter, and pre-monsoon. Many of the field parameters like dissolved oxygen (DO), pH, free carbon dioxide, conductivity, TDS, hardness, and alkalinity were analyzed in situ the field. For the measurement of the parameters such as water temperature, conductivity, and TDS, the multi-parameter water quality analysis instrument AQUAREAD 7000® was used. For dissolved oxygen, free carbon dioxide, hardness, and alkalinity the titrimetric method as given in APHA (2017) was used. The rest of the collected sample bottles were stored in the icebox and transported to the laboratory for further analysis of the remaining water quality parameters.

Laboratory analysis of the samples

In the laboratory, the parameters such as chloride and nitrate have been analyzed following the protocols of APHA 2005. For the analysis of chloride, the argenometric method was used. Nitrate analysis was done using the Kjeldahl method following (APHA, 2017).

Statistical analysis

All the statistical analyses were performed with Microsoft Excel 2007, PAST 4.03, and IBM-SPSS 22 software. The descriptive analysis such as mean and standard deviation is the conventional tool used for the analysis of water quality data (Mazinder Baruah & Singh, 2022; Mustapha et al., 2013) was

done using Microsoft Excel 2007. To know the relationship between WQI and the assigned quality scale used in the calculation of WQI, the Karl Pearson correlation was done using IBM SPSS 22 statistical software. To understand the different pollution sources in the different regions, the technique of principal component analysis is used (Wang et al., 2022). The principal component analysis was done by using PAST 4.03 software, and before this, the KMO-Barlett's test of sphericity was carried out using IBM-SPSS 22 software. To observe the trend for the analysis of changes in the average water quality data polynomial trend line is the best statistical tool (Roy & Majumder, 2022). So, the trend analysis was carried out using MS-Excel 2007, to know the difference in different parameters in different decades. To know the differences and the similarities among the different sampling sites, the cluster analysis is the best used statistical tool (Xiao et al., 2022). Among the different cluster analytical tools, the Bray Curtis cluster analysis is the most commonly used analytical method used by many of the researchers to classify the different sampling stations based on their physiological habitat (Asadi Sharif et al., 2021). The Bray Curtis cluster analysis was done by using PAST 4.03 statistical software. Discriminant analysis is a multivariate statistical analysis tool used for the classification of the individual sampling stations based on similarity or dissimilarity (Bilgin, 2018). To know the usability of the data the Shapiro–Wilk test was carried out. To distinguish the interannual and inter-station differences, the two-way ANOVA was used. The analysis of two-way ANOVA was also carried out using IBM-SPSS 22 software. To summarize the changes in the different parameters in different decades at different sampling sites, the discriminant analysis was done using IBM-SPSS 22 software.

Calculation of WQI

The water quality index (WQI) is the best statistical tool used to rate the status of the river water, which is influenced by multiple stressors. The index was calculated by using the method given by (Deshmukh & Aher, 2016). For the calculation of the water quality index, data of 8 chemical parameters viz. pH, dissolved oxygen (DO), specific conductivity, total alkalinity,

total dissolved salts (TDS), total hardness, chloride, and nitrate were used. The selection of the parameters for the study is based on the data available from the secondary sources and their significance. During the selection of the parameters, the importance and significance of the parameters have also been taken into account. All the selected parameters have individual significance based on drinking water guidelines BIS 2012. pH is the most important chemical parameter; its alteration can cause various gastrointestinal diseases to the users and various ravages to the aqua biotic community as well (EPA). Majority of aquatic organisms lacks the advanced form of the respiratory system to respire, so they use dissolved oxygen (DO) for the purpose. DO can affect the aquatic habitat by making various alterations in the ecological niche. Alteration in the DO can degrade the water quality status of the riverine system. Specific conductivity, TDS, hardness, chloride, and nitrate are the best-described pollution-indicating parameters used for the analysis of riverine water quality (Manna et al., 2013). Total alkalinity signifies the buffering capacity of the river which has been used for the study (Hare et al., 2020). For the calculation of WQI, the different parameters were assigned a specific weight value (AW) (Table 2) on a scale of 1 to 5 where 1 is for least influencing water quality parameter and 5 for the parameter which has the highest impact on the water quality (Horton, 1965). The weight for the individual parameters was assigned the weight as per their relative significance as drinking water (Dimri et al., 2021a). However, the relative significance of the parameters may vary individually as per the studied ecological environment. So, there are many limitations for assigning the weight to the individual parameters

(Lumb et al., 2011). After assigning the AW, the relative weight was calculated by using Eq. (1)

$$AW = RW \div \sum_{i=0}^n RW \quad (1)$$

where RW is relative weight and AW is weighted value.

In the third step, the quality rating scale (Q_i) was obtained by dividing the observed concentration (C_i) of the sample with the standard proposed for the parameter (S_i) and then multiplying it by 100 (Eq. (2)).

$$Q_i = \frac{C_i}{S_i} \times 100 \quad (2)$$

For quality rating of dissolved oxygen and pH, Eq. (3) was used:

$$Q_{ipH, DO} = \left(\frac{C_i - V_i}{S_i - V_i} \right) \times 100 \quad (3)$$

where Q_i , quality rating; C_i , observed value of water quality; S_i , standard value of the parameter; V_i , ideal value, i.e., for pH it is 7, and for dissolved oxygen, it is 14.6.

In the fourth step, the sub-indices values (SI_i) were calculated using Eq. (4):

$$SI_i = W_r \times Q_i \quad (4)$$

In the last step, the WQI was calculated using the sub-index (SI_i) Eq. (5):

$$WQI = \sum_{i=1}^n SI_i \quad (5)$$

After calculation of the WQI, the obtained values were classified according to (Brown et al., 1970) (Table 3).

Table 2 Relative assigned weight for WQI calculation

Parameters	AW (assigned weight)	Relative weight
pH	3	0.125
TDS	3	0.125
DO	3	0.125
TH	3	0.125
TA	2	0.083
EC	4	0.167
CL	3	0.125
NO ₃	3	0.125
$\sum AW$	24	

Results

Trends and multidecadal changes in the water quality parameters

The mean dissolved oxygen, as exhibited in Fig. 3 was 7.42 ppm in the year 1960–1961 which reduced to 5.40 ppm in the year 1987–1988, but it improved to the average value of 7.48 ppm during 2001–2006 and 7.23 ppm during 2015–2019. Out of the studied 6 sampling sites, the Kanpur and Varanasi exhibited critically low dissolved oxygen with an average value of 5.98 ppm and 6.01 ppm respectively. Among all the sampling

Table 3 Range of WQI and relative status (Brown et al., 1970)

Range of WQI scale	Water quality status
0–25	Excellent
26–50	Good
51–75	Poor
76–100	Very poor
Above 100	Unsuitable

stations, Kanpur even exhibited a low DO value of 1.80 ppm during 1987–1988; low DO of 2.20 ppm of DO was observed at Varanasi during 1987–1988. Patna, Bhagalpur, and Farraka always show DO values of >6.23 ppm. In the subsequent period, however, with the average DO value of 6.96 ppm. At all the stations, the average DO was good as per standard permissible limits for drinking water given by BIS 2012, i.e., >6 ppm. However, during the years 1987–1988, the lower average DO was observed at Kanpur and Varanasi where the average DO was 1.80 ppm and 2.20 ppm respectively during the time. However, the DO value was higher than the threshold limit in point of the fishery as of 3.0 ppm (FAO) in all the decades. Except for a few exceptions, i.e., during 1987–1988 lower, DO was observed at Kanpur and Varanasi.

pH is the measurement of acidity and the basicity of the solution. The studied stretch of the river Ganga revealed higher pH values which imply alkaline riverine water (Fig. 4). The average pH during 1960–1961 was 8.02 which reduced to 7.74 in 1987–1988. But again, the pH value increased with an average value

of 8.15 in 2001–2006, and 8.23 in 2015–2019. Among all the studied sites in the entire study period, i.e., from 1960–1961 to 2015–2019, the highest average pH value of 8.21 was recorded at Farraka, while the lowest pH of 7.88 was recorded at Kanpur. Out of the entire data matrix, the relatively low pH was recorded at Kanpur (7.2) and Varanasi (7.4) during 1987–1988. The values of pH in all the decades and at all the sampling stations were within the standard limits given by BIS, 2012 for drinking water purposes and that of FAO for the point of fisheries.

The average free carbon dioxide (FCO₂) in the studied river stretch varied from 1.54 to 6.06 ppm during 1960–2019 (Fig. 5). A relatively higher average FCO₂ value of 6.06 ppm was recorded during the year 1987–1988, which is due to the higher content of 12.4 ppm at Kanpur and 8.8 ppm at Varanasi. The relatively higher content of FCO₂ has observed 4.6 ppm at Prayagraj. Among all the sites the highest average FCO₂ during 1960–1961 to 2015–2019 was recorded 4.53 ppm at Kanpur and the lowest was recorded 2.18 ppm at Prayagraj. At all the stations, free CO₂ was in the permissible range prescribed for drinking water as well as for fisheries (Kumar & Puri, 2012).

The average value of total alkalinity in the river system was found in the range of 138 to 172 ppm during 1960–2019 (Fig. 6). A distinct increase in the values of total alkalinity was recorded in almost the entire stretch during 1987–1988 to 2001–2006 and thus, the average value also increased to 166 ppm in 1987–1988 and 172 ppm in 2001–2006. A decreasing trend in the parameter was, however, recorded during

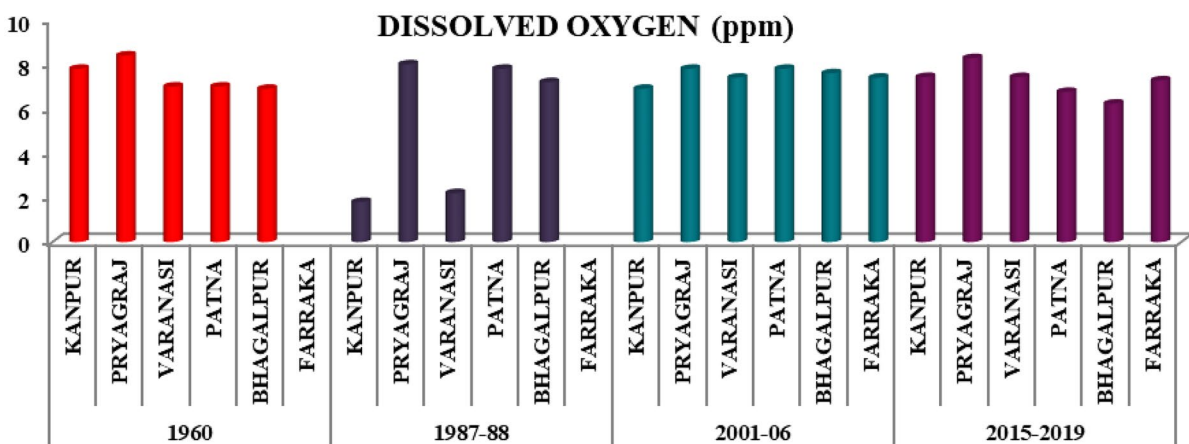


Fig. 3 Variation of Dissolved oxygen at different sampling sites in different decades

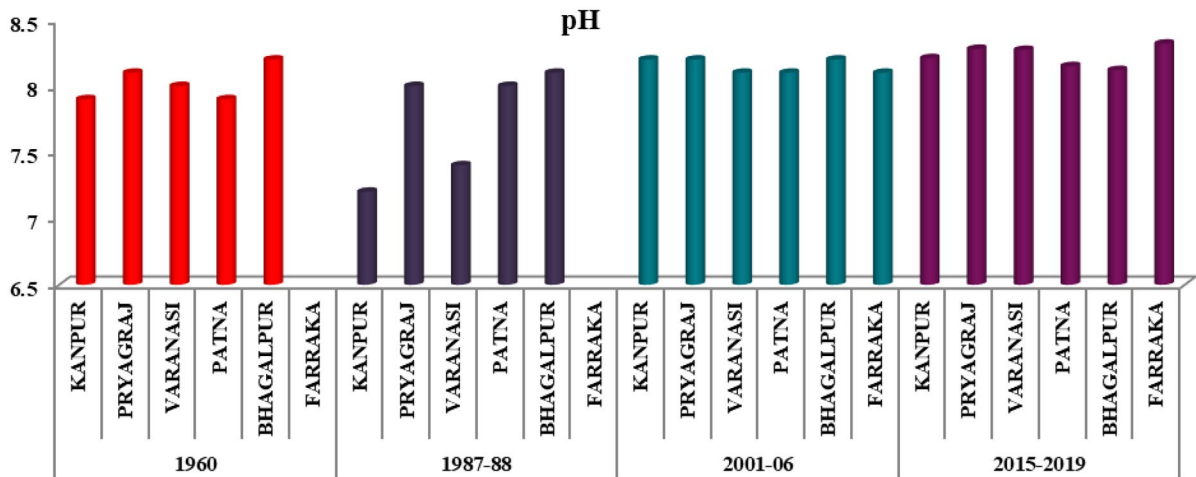


Fig. 4 Variation of pH at different sampling sites in different decades

2015–2019 resulting in an average value of 144 ppm. Among all the studied sites, the average total alkalinity value during 1960–1961 to 2015–2019 was found highest of 169.13 ppm at Kanpur while the lowest was found 124.73 ppm at Farakka. Alkalinity at all the stations was also found to be within the permissible range given by BIS, 2012 as well as that of FAO considered for fisheries.

The average specific conductivity of the riverine system varied from 282 $\mu\text{S}/\text{cm}$ to 424 $\mu\text{S}/\text{cm}$ during 1960–1961 to 2015–2019 (Fig. 7). A gradual increasing trend in the average value of specific conductivity was prominent with time as represented in Fig. 7. Majority of the sampling sites exhibited a similar trend of the increased value of the parameter, which may be possibly due to the increasing industrial effluent

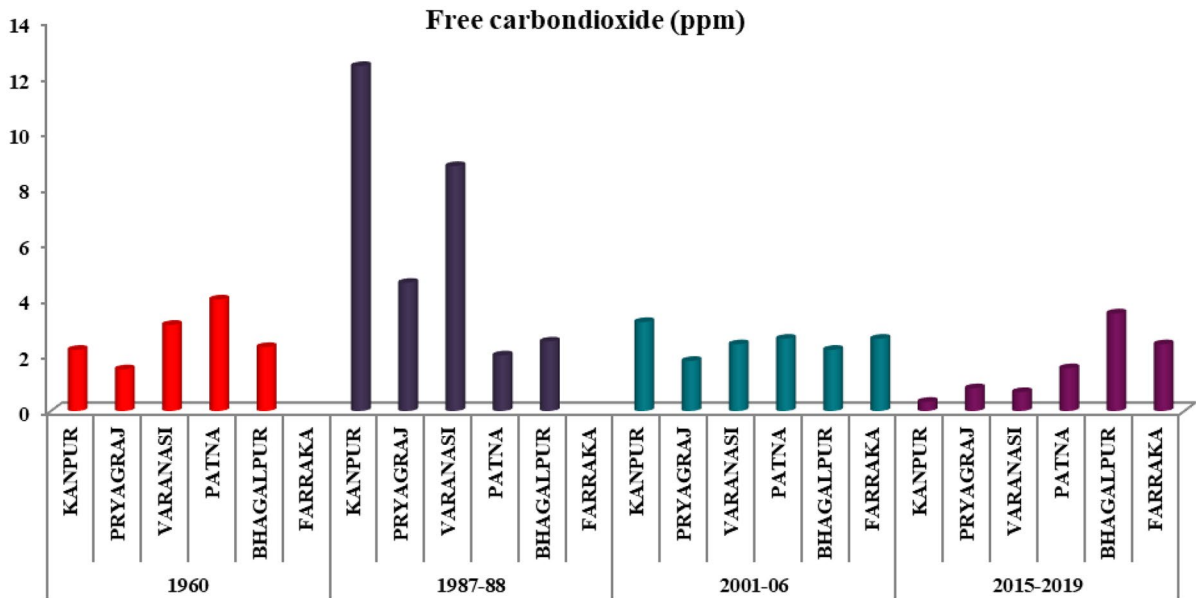


Fig. 5 Variation of free carbon dioxide at different sampling sites in different decades

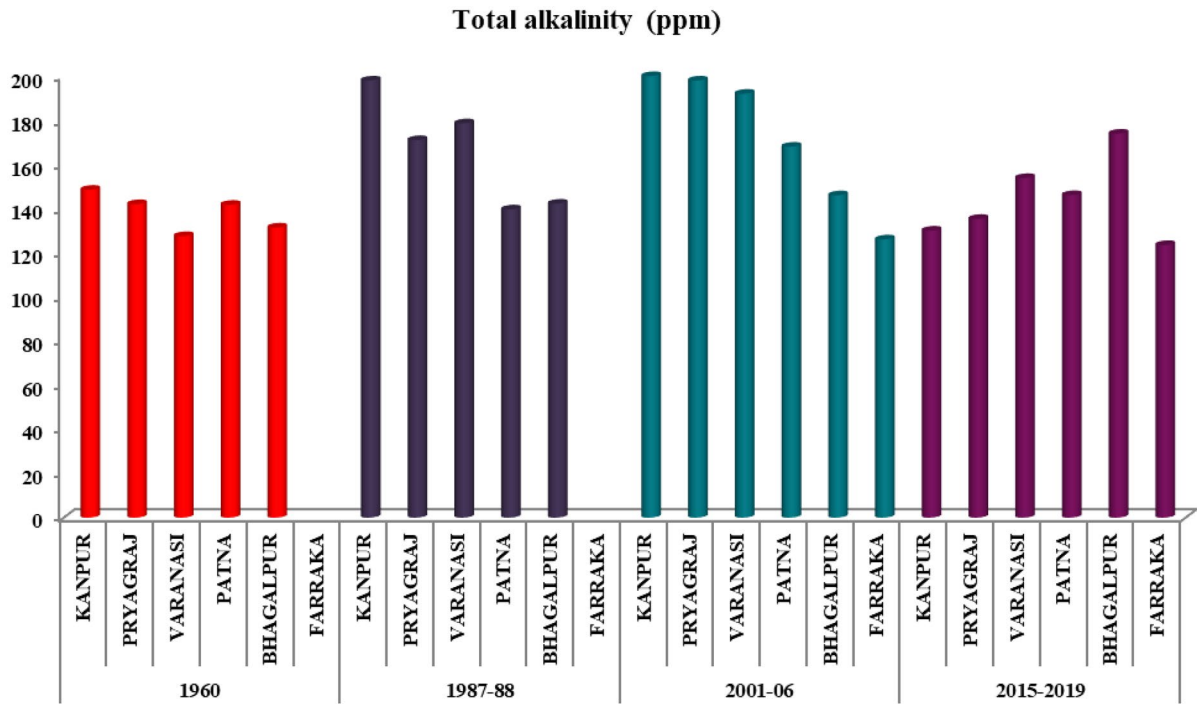


Fig. 6 Variation of total alkalinity at different sampling sites in different decades

with higher ionic load over the years along with the increased entry of sewages from domestic sources due to ever-increasing population. Higher conductivity values were observed at Kanpur, Prayagraj, and Varanasi,

especially between the years 1987 and 2006. But slight improvement is observed during 2015–2019. As per BIS, 2012, the observations were also limited within the permissible range (Kumar & Puri, 2012).

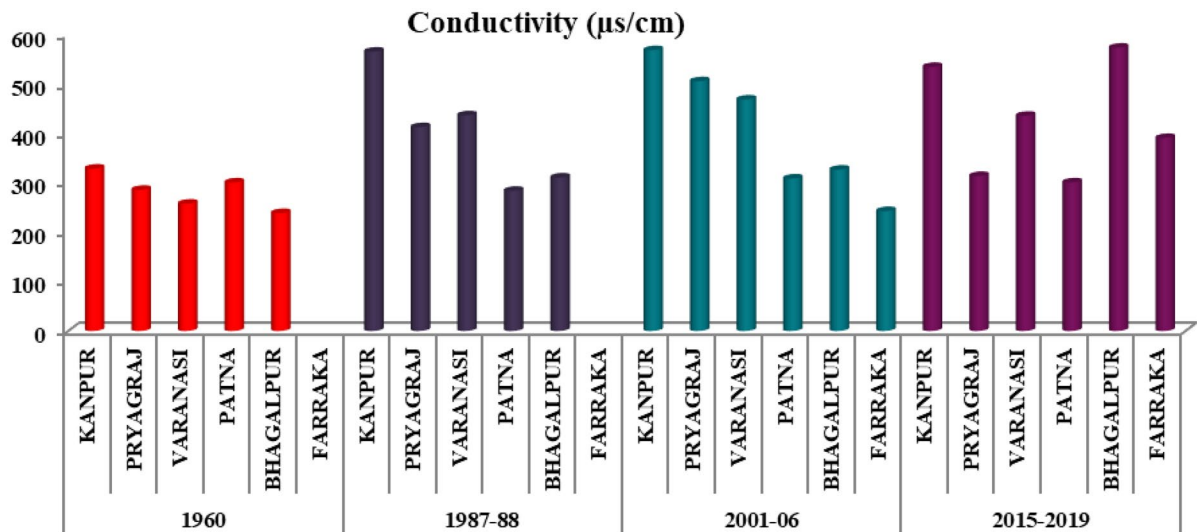


Fig. 7 Variation of conductivity at different sampling sites in different decades

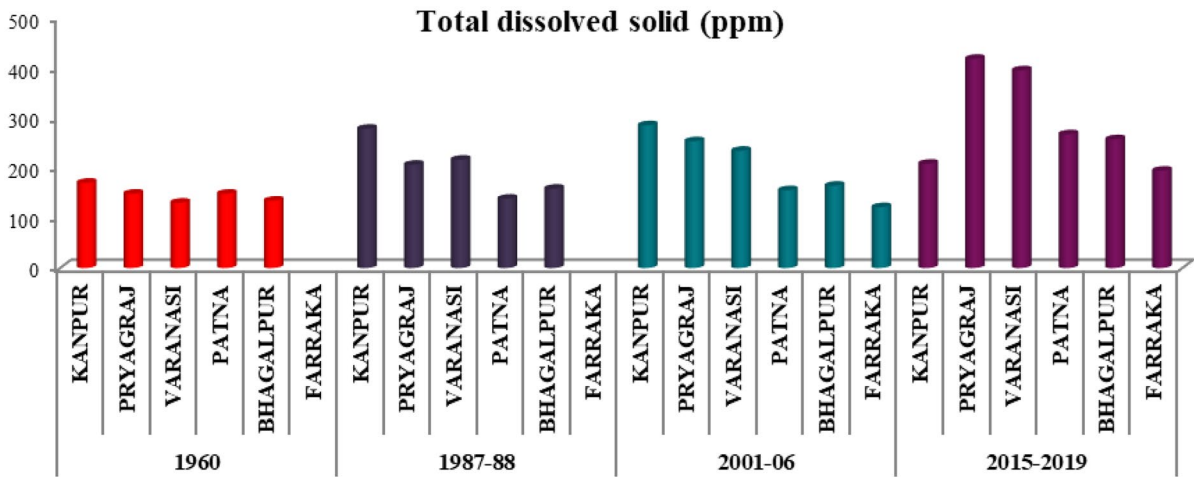


Fig. 8 Variation of TDS at different sampling sites in different decades

The average TDS value of the riverine system varied from 146 to 289.93 ppm. With an increasing trend from 1960–1961 to 2015–2019 (Fig. 8). In 1960–1961, it was found 146 ppm which rose to 199 ppm in 1987–1988, 202 ppm in 2001–2006, and 290 ppm in 2015–2019. The majority of the sampling sites exhibited a similar trend of the increasing value of the parameter with time. The 2015–2019 data in the Prayagraj to Farakka stretch exhibited prominently increased value of the parameter. The standard permissible value of TDS given by WHO is <300 ppm. So in some cases, the higher values were observed at Prayagraj and Varanasi, during 2015–2019.

The average hardness of the river system was found to be in the range of 118 to 148 ppm during the reported period. It increased from 118 ppm in 1960–1961 to 144 ppm in 1987–1988; 148 ppm in 2001–2006, but the value was observed to be reduced to 138 ppm in 2015–2019 (Fig. 9). A distinct increasing trend was prominent in the sampling sites with time up to 2001–2006. Hardness at all the stations was within the standard permissible range, i.e., <300 ppm as given by BIS 2012.

The chloride content in water is a good indicator of anthropogenic activities in freshwater systems. In the present study, the average chloride content was observed 13 ppm in 1960 which increased to 23 ppm

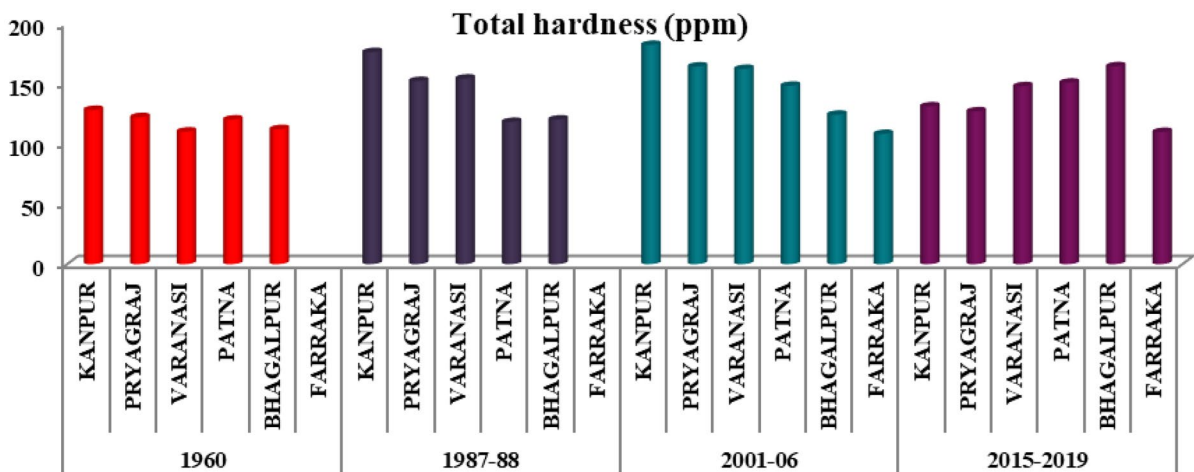


Fig. 9 Variation of Total hardness at different sampling sites in different decades

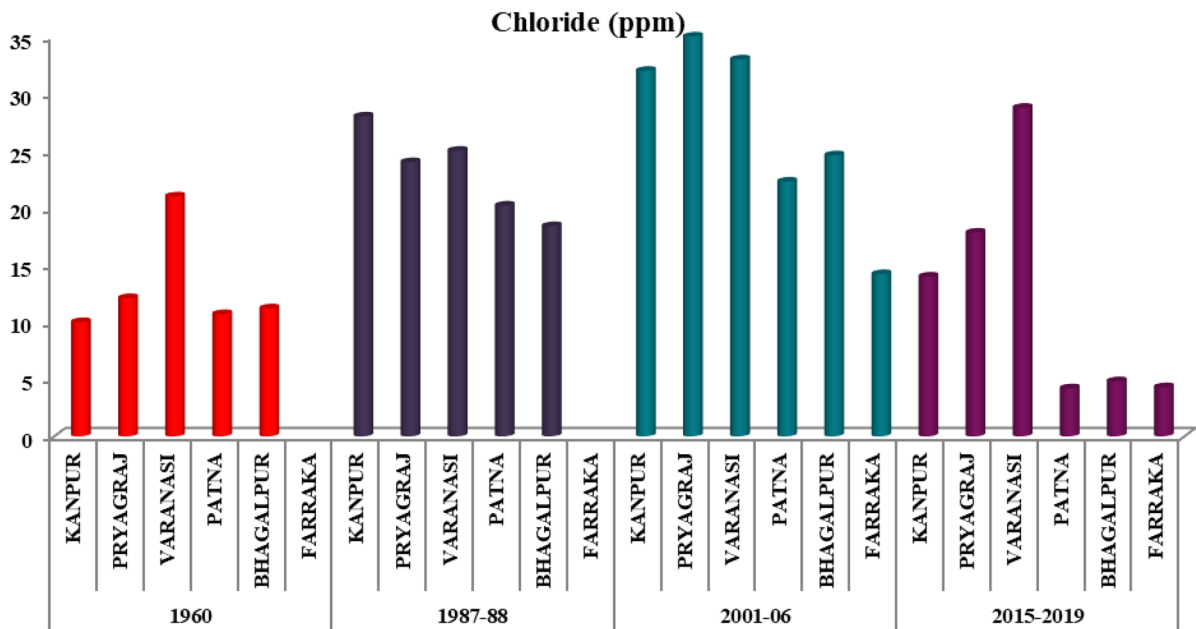


Fig. 10 Variation of chloride at different sampling sites in different decades

in 1987–1988 and 27 ppm in 2001–2006. The value, however, reduced to 12 ppm in 2015–2019 (Fig. 10). The majority of the sampling sites exhibited a similar trend in the parameter. At all the stations, however, the chloride content was within the permissible range of < 250 ppm.

The average nitrate content in the water of river Ganga varied from 0.14 to 0.70 ppm. The value of nitrate rose from 0.14 in 1960 to 0.22 ppm in 1987–1988. It got reduced to 0.16 ppm in 2001–2006. The observed nitrate value during 2015–2019 was 0.70 ppm. A prominent increase in value of the parameter was recorded in the Kanpur to Varanasi stretch during 2015–2019 (Fig. 11). At all the sampling stations, however, the nitrate was within the permissible range of < 45 ppm as prescribed for drinking water as well as for the survival of aquatic animals.

Decadal changes in the trend of different water quality parameters

The trend of different water quality parameters indicated greater fluctuations. The polynomial trend line for mean dissolved oxygen (Fig. 12) showed, maximum lowering of DO values has been observed during 1987–1988,

i.e., $(5.4 \pm 3.12 \text{ ppm}) (R^2 = 0.30)$. However, in the rest of the decades, the average DO values were > 7 ppm. Similar to DO, the pH values also showed the fluctuating trend ($R^2 = 0.616$) as lower pH values were observed during 1987–1988. Higher pH values were, however, observed during 2001–2006 and 2015–2019 (Fig. 12). The FCO_2 showed a fluctuating trend over the decade ($R^2 = 0.60$). Relatively higher FCO_2 , i.e., 6.06 ± 4.44 has been reported during 1987–1988. The mean total alkalinity was found highest during 2001–2006. The increment in the total alkalinity values has been observed from 1960 to 2001–2006. Then, the decreased value of total alkalinity has been observed during 2015–2019 ($R^2 = 0.991$). Dissimilar to other parameters the conductivity ($R^2 = 0.924$) and TDS ($R^2 = 0.913$) were observed in increasing trend with time. The hardness and chloride also followed the increasing trend from 1960 to 2001–2006, but the values of hardness and chloride were observed to be decreased during 2015–2019. The nitrate showed a fluctuating trend as the increased nitrate value was found from 1960 to 1987–1988, while a relatively lower value was observed during 2001–2006. The value of nitrate exhibited a significantly increasing trend during 2015–2019 with a recorded average content of $0.70 \pm 0.40 \text{ ppm}$.

Assessment of the sampling sites using the water quality index

In the study, the water quality index of selected six stations located in the middle and lower stretch of the world’s 5th largest river system “Ganga” was calculated focusing on the decadal changes in the river system (Fig. 13). The lowest average value of WQI of the entire river system as measured at 6 different sampling stations in the middle and lower stretch of the river Ganga during 1960–1961 was 69.14 (Fig. 14). It’s value was observed 95.08 during 1987–1988 (Fig. 15). The WQI further increased to 113.40 during 2001–2006 (Fig. 16). However, subsequently, its value decreased and the observed WQI was 106.48 during 2015–2019 (Fig. 17 and Table 4). Like the average WQI values, the lowest and highest WQI values also differed at individual sampling sites in different decades. During 1960–1961 lowest values of WQI was observed 67.1 at Varanasi while the highest of 70.98 at Bhagalpur its value increased during 1987–1988. The observed maximum WQI during 1987–1988 was 105.81 at Bhagalpur, and the observed lowest WQI value was 86.34 at Kanpur. The observed maximum WQI during 2001–2006 was 131.63 at Kanpur, and the minimum value was observed 94.86 at Farakka. The maximum value of WQI during 2015–2019 was

Fig. 12 Change in the trend of different water quality parameters over the decades

125.75 at Varanasi, while the lowest observed WQI during the period was 95.02 at Patna. The rate of change, however, differed from one sampling site to the other. The maximum variation was recorded at Varanasi indicating the most impacted site with its WQI values of 67.1 during 1960–1961, increased to 93.57 during 1987–1988; reached its maximum value of 125.75 during 2015–2019. The variation at Bhagalpur and Patna was recorded to be the least .

Relation between WQI and assigned quality scale and increase in population

To observe, the relation between WQI and assigned quality scale the Karl Pearson correlation was carried out. The observed Karl Pearson correlation showed that there was a significantly positive correlation ($P > 0.05$) and ($P > 0.01$) observed between various studied parameters and WQI. The positive correlation was observed with total alkalinity, conductivity, TDS, hardness, and chlorinity (Table 5) and (Fig. 18), while the descriptive analysis showed that an increase in the population has also adversely affected the WQI at all the studied sites and in three decades, i.e., starting

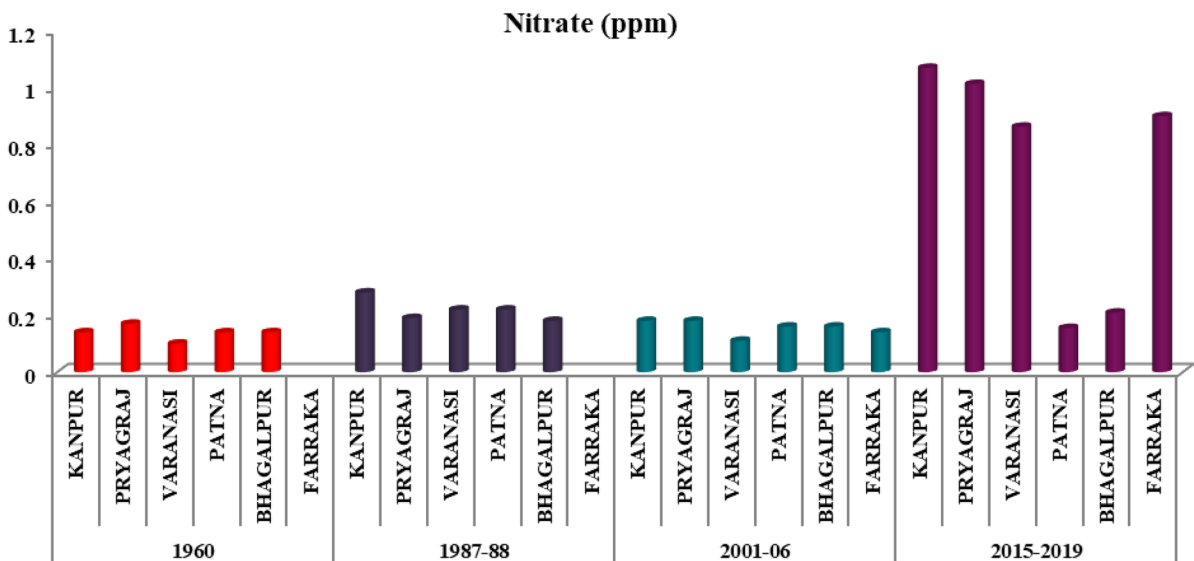
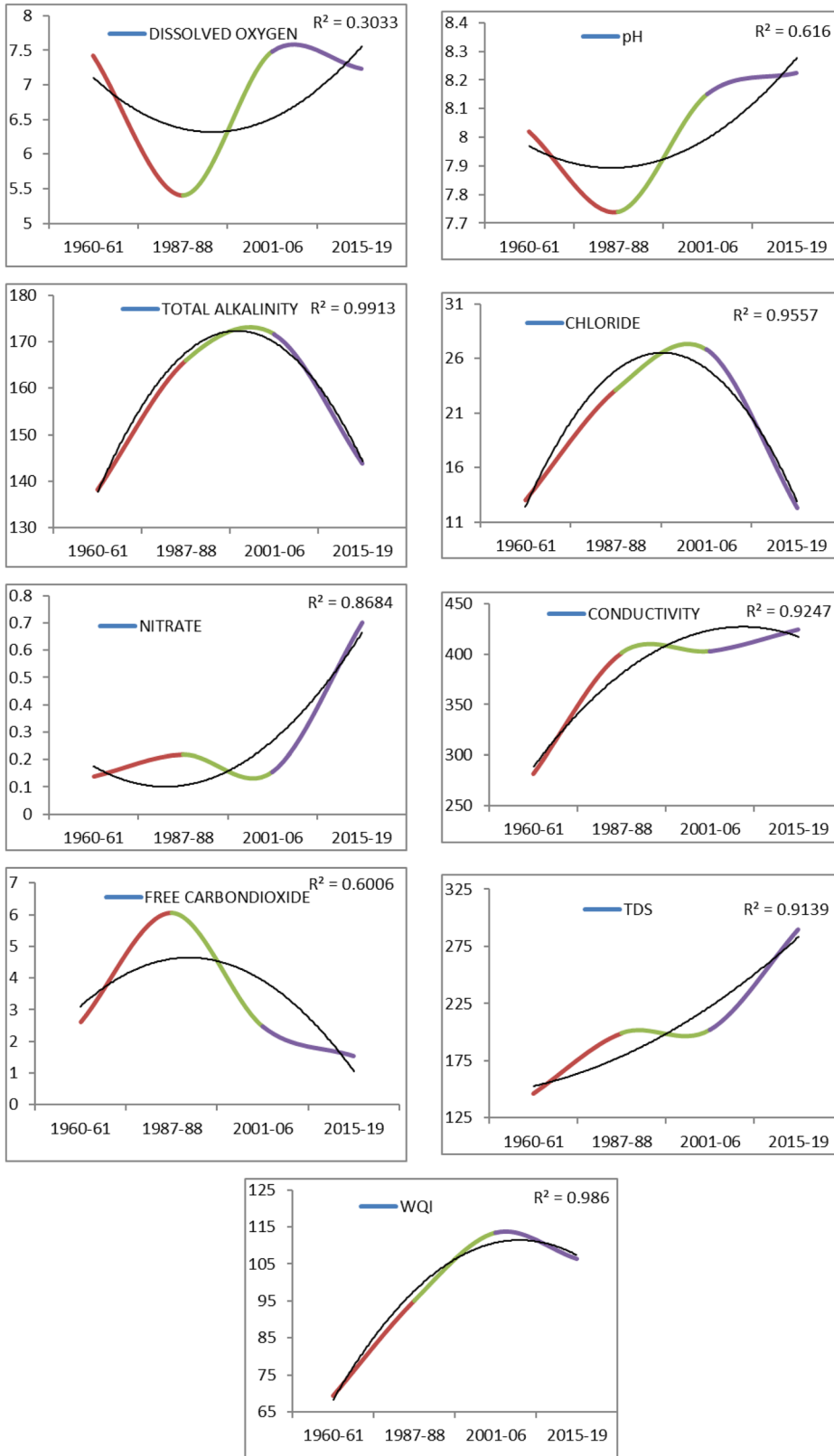


Fig. 11 Variation of Nitrate at different sampling sites in different decades



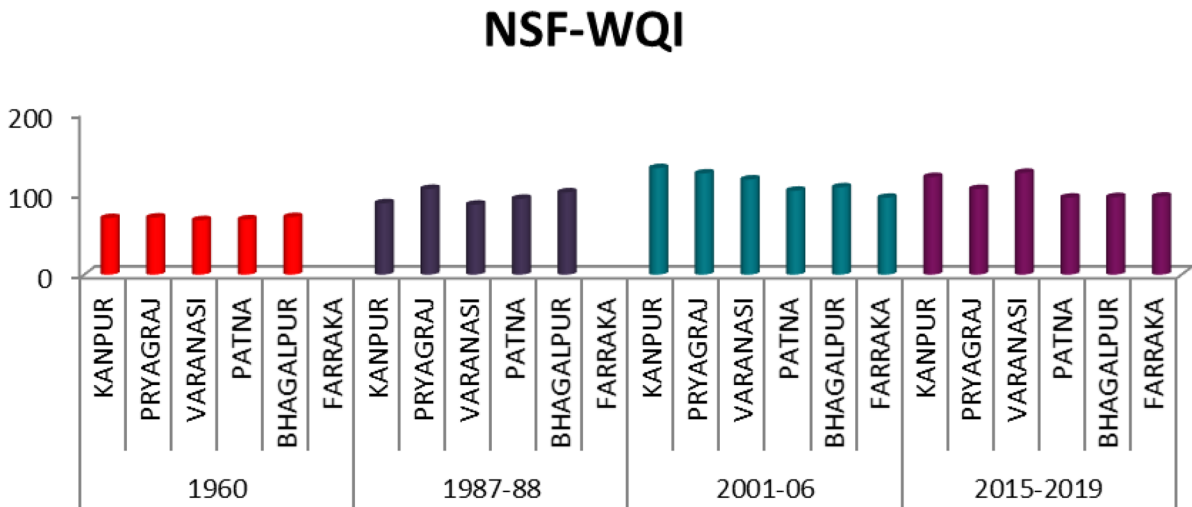


Fig. 13 Variation of NSF-WQI at different sampling sites in different decades

from 1960–1961 to 2001–2006 (<http://www.macrotrends.net>) (Fig. 19). But during 2015–2019, the value of WQI relatively decreased at all the sampling sites except at Varanasi (Fig. 19).

Principal component analysis

To know the major influencing water quality parameters during the entire period of 60 years, a PCA bi-plot was made with selected 9 different water quality parameters (Fig. 20). Before PCA analysis, KMO- Barlett’s test was performed in which the KMO=0.059 and significance of the Barlett test of sphericity was $p=0.00$, in which the variance percentage, where the eigenvalue > 1 is extracted. In the analysis, there are 3 PCs extracted in which PC 1 is having the maximum variance, i.e., 46.40%. And the combined variance % of all the 3 PC’S is 84.90% (Table 6). In the PC1, the strong positive loading was observed with free carbon dioxide ($r=0.88$), conductance ($r=0.82$), total hardness ($r=0.82$), chloride ($r=0.60$), while strong

negative loading was observed with dissolved oxygen ($r=-0.77$) and pH ($r=-0.73$). In the 2nd PC, the strong positive loading was observed with pH ($r=0.59$), TDS ($r=0.75$), and nitrate ($r=0.62$). In the 3rd PC, strong negative loading was with nitrate ($r=-0.71$).

Cluster analysis

Bray–Curtis cluster similarity was performed to know the similarity in the water quality status among the different sampling stations in the different decades. In 1960–1961 among all the sampling sites, the cophenetic correlation was 0.81. In the analysis, it was found that Prayagraj and Patna exhibited a maximum similarity of 98%. Varanasi and Bhagalpur are having similarity of 97% of similarity. Kanpur exhibited the similarity of 95% with Prayagraj and Patna. Varanasi and Bhagalpur are having the least similarity with Kanpur (Fig. 21). In 1987–1988, the cophenetic correlation was 0.81. During the period, the maximum

Table 4 The observed water quality index at different studied sites in different decades

Sl. no.	Station	WQI 1960	WQI 1987–1988	WQI 2001–2006	WQI 2015–2019
1	Kanpur	69.71	88.02	131.63	120.56
2	Pryagraj	70.39	105.81	125.00	105.74
3	Varanasi	67.10	86.34	117.53	125.75
4	Patna	68.02	93.57	103.56	95.02
5	Bhagalpur	70.98	101.55	107.80	95.64
6	Farraka	NA	NA	94.86	96.17

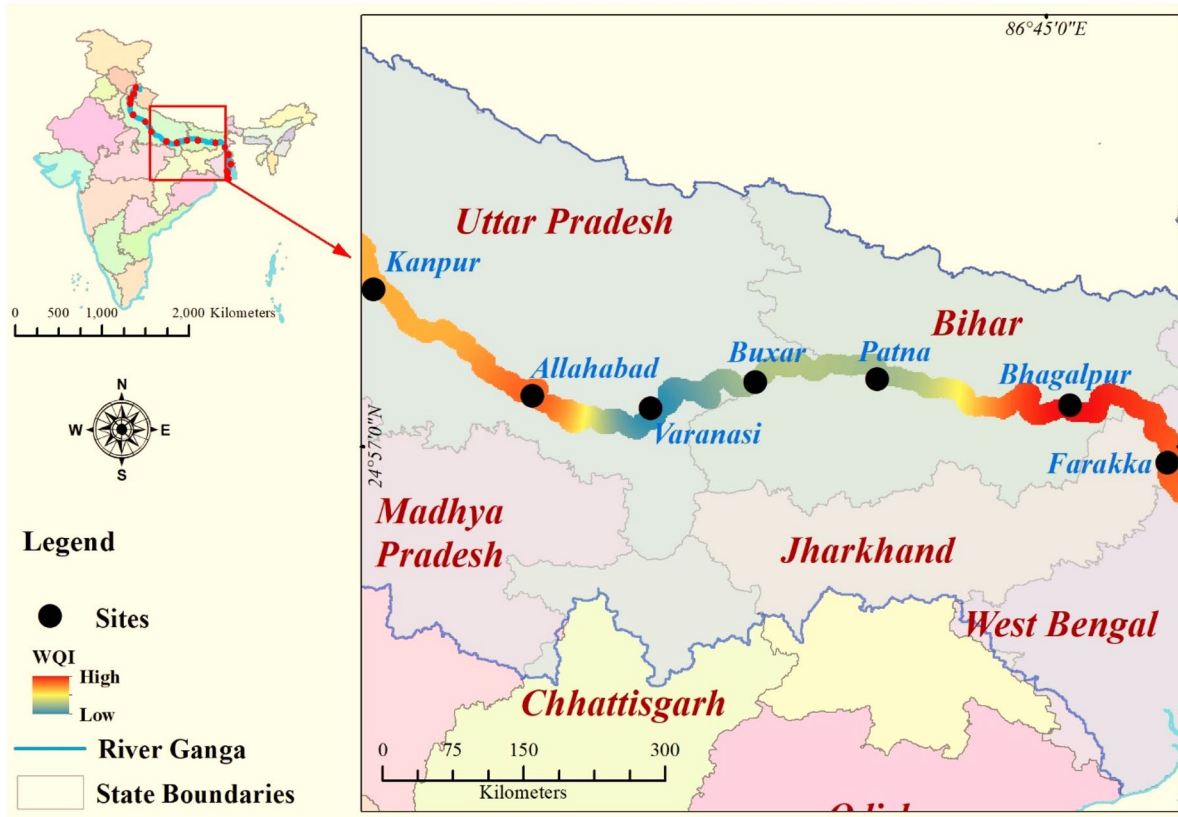


Fig. 14 WQI at different sampling sites between 1960 and 1961

similarity of 96% was observed between Pana and Bhagalpur. Prayagraj and Varanasi are also having a similarity of 96%. Kanpur is having a maximum similarity of 88% between two stations, i.e., Varanasi and Prayagraj (Fig. 22). During 2001–2006, the cophenetic correlation was 0.85. The maximum similarity of 96% was observed between Prayagraj and Varanasi. Patna and Bhagalpur have 95% of similarities. Farakka was having a maximum similarity of 87.5% with Patna and Bhagalpur, while Kanpur was having a similarity of 93.75% with Prayagraj and Varanasi (Fig. 23). Between 2001 and 2006, all the stations formed two major clusters. Between 2015 and 2019, the cophenetic correlation was 0.68. The maximum similarity of 91% was observed with Kanpur and Bhagalpur. Prayagraj and Varanasi are having a similarity of 90.5%. Patna and Farakka are having similarities of 88%. There are a total of 3 major clusters formed. The Patna and Farakka are having more similarities

with Bhagalpur and Kanpur, while less similarity was observed with Prayagraj and Varanasi (Fig. 24).

Two way ANOVA

To know the significance of the change in the different water quality parameters over the decades at different sampling stations, two-way ANOVA was carried out. The result showed that among the decades the variation was observed for two of the parameters, i.e., TDS and conductivity (Table 7). All the rest of the parameters have no significant variation over the decades and among the different sampling stations.

Discriminant analysis

Canonical discriminant analysis along with MANOVA was applied for decadal discrimination of water quality. The Wilk’s test showed statistical significance (test

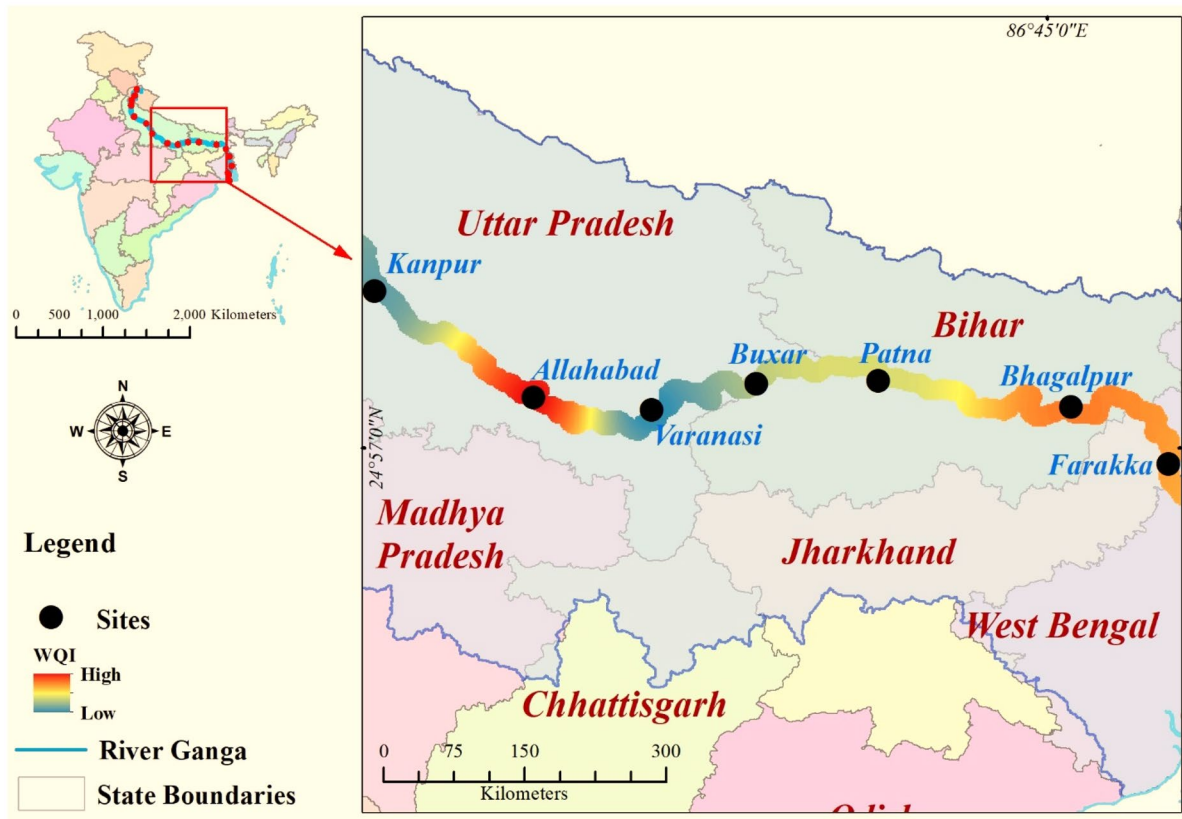


Fig. 15 WQI at different sampling sites between 1987 and 1988

statistic=0.228; approx. $F_{9,12}=3.47$; p -value=0.0247) that water quality discriminated decades. The magnitude of the correlation of a parameter with canonical scores was used as the relative importance for discrimination. Accordingly, the order discriminating importance were as follows: TDS>nitrate>pH>conductivity> FCO_2 >hardness>total alkalinity>dissolved oxygen>chloride. The contributions of dissolved oxygen, total alkalinity, and chloride were almost insignificant (Fig. 25 and Table 8). The canonical score depicted a decreasing trend over the decade.

Discussion

Generally, the quality of water in any open water body including rivers is influenced by man-made activities (Paul et al., 2021). The health of the river Ganga is accordingly influenced by the rise in population and increased anthropogenic activities (Ansari & Kumar,

2021). The present study mostly reflects the multi-decadal variation of important physicochemical water quality of the river Ganga from 1960 to 2019, depicting the water quality index and how it has changed over the years. The secondary data collected from the ICAR-CIFRI bulletin and extensive study from the present team under the sponsored project of the National Mission for Clean Ganga during 2015–2019 have been put together for the prediction of the Ganga health which will bring its ecosystem health point of view and focus on the synergistic approach for its holistic development that Government of India has already initiated for several years and will be taking in near future.

Dissolved oxygen (DO) is the most important parameter in the aquatic ecosystem. In its deficiency, the normal functioning of the aquatic ecosystems is hampered; as is reflected in the biological and physiological status of the riverine ecosystems (Kamboj & Kamboj, 2019). Thus, long-term monitoring of the

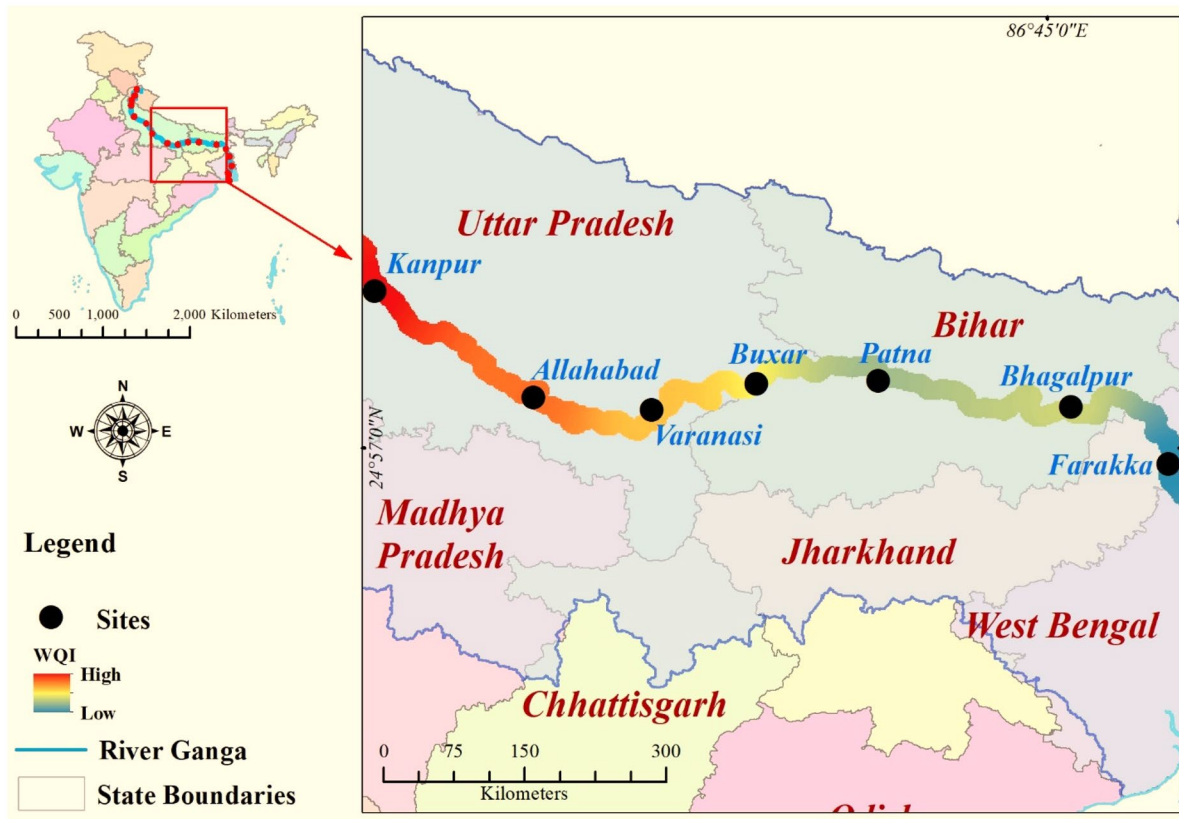


Fig. 16 WQI at different sampling sites between 2001 and 2006

parameter is essential for the assessment of riverine ecosystems and their health (Kannel et al., 2007). Initially, the average DO was observed at a good level of 7.42 ppm during 1960–1961 which got reduced to 5.40 ppm in 1987–1988, maybe due to more and more entry of organic matter enriched sewage, industrial effluents, and reduced riverine flow (Cox & Whitehead, 2009). The Kanpur and Varanasi stretches were the most affected sites where critically low levels of DO were detected. The impact of enhanced industrialization, less riverine flow due to the construction of dams and barrages, on DO has been explained in several studies and has been described by Carmichael (1996) in River Nitra of Slovakia and (Sharma et al., 2008) in river Narmada. However, after 1987–1988, again a significant increase in DO was recorded and the average DO reach > 7 ppm, which is a symbol of good riverine health. This was mostly due to the implementation of several corrective measures by the Ganga Action Plan (Vass et al.,

2010) and subsequently by the National Mission for Clean Ganga and other related activities.

Water pH indicates the degree of basicity and acidity of the water (Kamboj & Kamboj, 2019). The Indian Standard specification of pH for drinking water, i.e., BIS 2012 (BIS, 2012) mentioned that it should be between 6.5 to 8.5. The most productive aquatic systems have alkaline pH and a similar observation of desired average pH range of 7.74 to 8.23 was recorded from 1960 to 2019 in the present study indicating that the riverine health was congenial to the aqua life and several biological activities would proceed to happen without much stress into the riverine habitat.

The FCO₂ is the important parameter responsible for maintaining the better health of the river as many aquatic autotrophs utilize the FCO₂ for the process of photosynthesis (Falkowski et al., 1985). In the study, it has been observed that all the regions possess the desirable range of FCO₂, although a higher range of FCO₂ was observed at Kanpur and Varanasi,

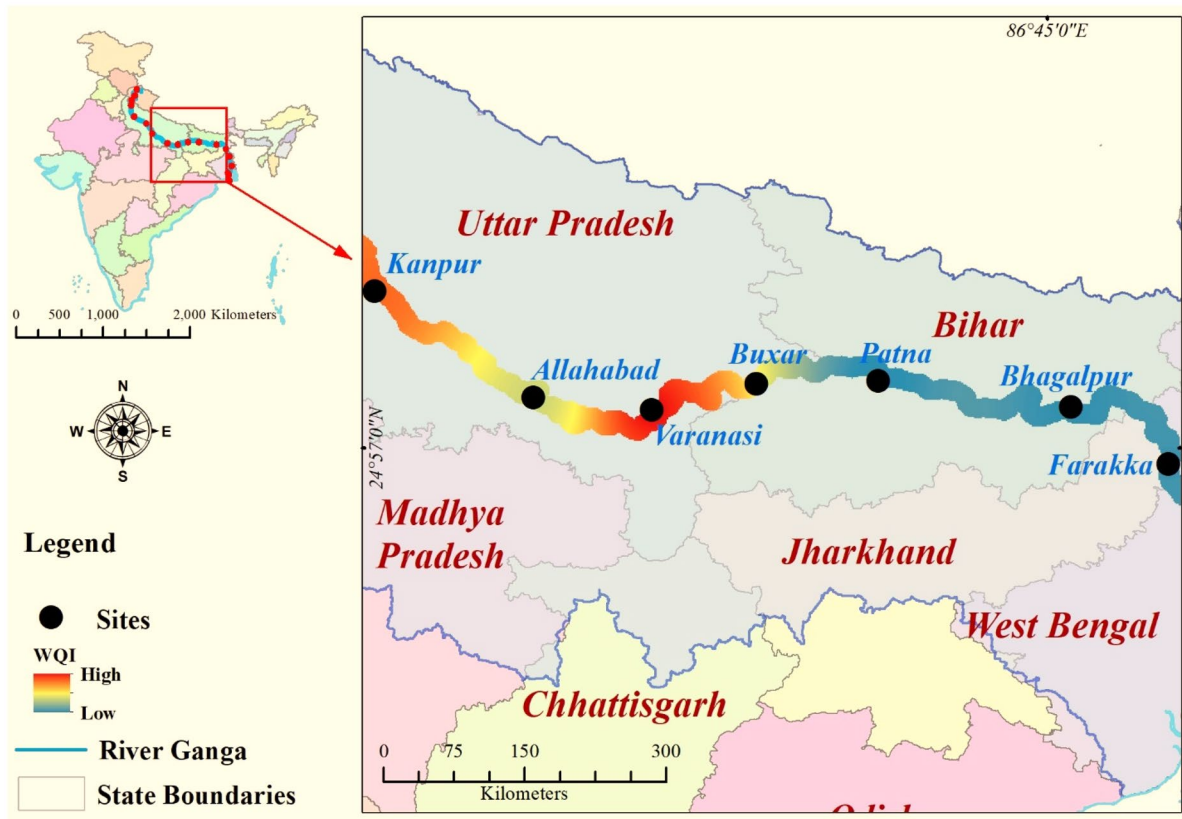


Fig. 17 WQI at different sampling sites between 2015 and 2019

which may signify relatively increased pollution status of the river. The FCO_2 is also considered as one of the pollution indicators in the riverine environment (Manna et al., 2013).

Riverine alkalinity expresses the dominance of the basic cations over their anionic counterparts and thus, alkalinity can neutralize the acidic behavior of the aquatic system (Olin Neal, 2001). It is contributed by the impact of weathering of rocks and various anthropogenic activities (Tappin et al., 2018). In the present study, the average total alkalinity has been noted to rise from 138 ppm in 1960–1961 to 172 ppm in 2001–2006. But it got reduced to 144 ppm during 2015–2019 reflecting the positive impact of the much-needed National Action Plan of the Government of India to restore the aquatic life of river Ganga by increasing the habitat suitability chemical parameters and reducing the pollution threats into the system. However, as per the recommended standard of BIS, 2012, it was within the safe range of <200 ppm.

Further desired alkalinity is responsible for the recruitment of the many fish species for their larval development, which would be directly beneficial for many aquatic species and overall economic development in the river (Parida et al., 2022).

Specific conductivity is the representation of the content of cations and anions which includes the desired nutrient ions also. Thus, under freshwater conditions, the productive systems have moderate levels of specific conductivity. However, the higher values mostly represent the accumulation of salts from the incoming sewage and effluents. In the present study, the observed average specific conductivity during 1960–1961 was 282 $\mu\text{S}/\text{cm}$ which increased up to 424 $\mu\text{S}/\text{cm}$ might be due to the increased pollution load received from the growing population (Liyana & Yamada, 2017). Most of the cities on the bank of river Ganga have a population growth of around 25–30% per decade. The growing populations have contributed to the unregulated city discharges into the river which

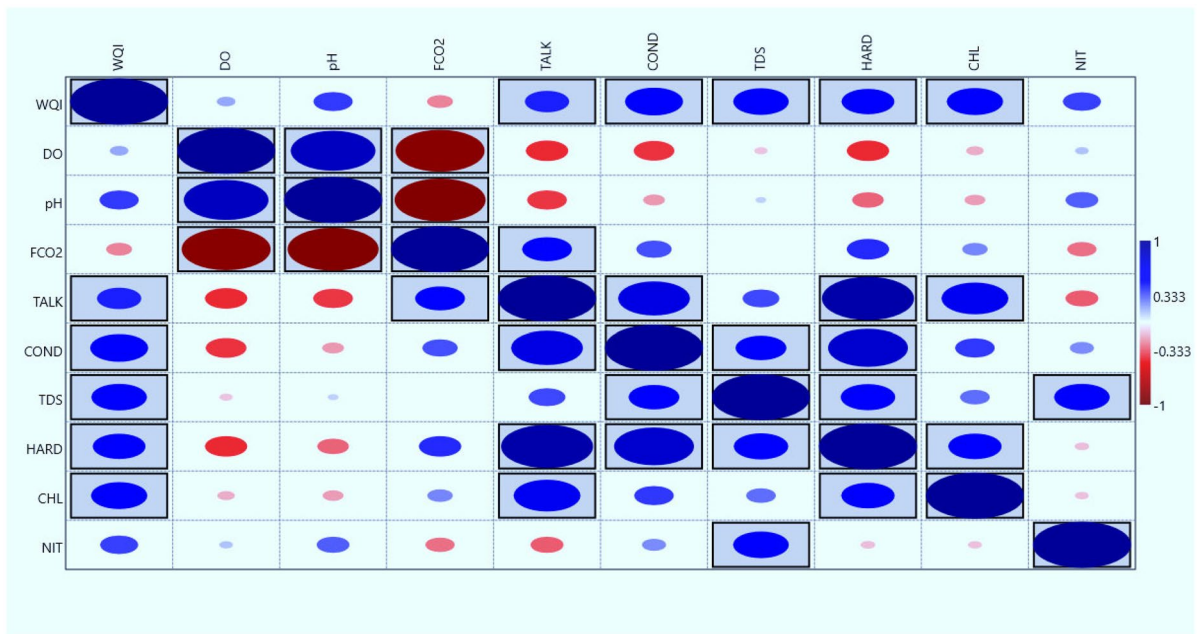


Fig. 18 Correlation between WQI and different water quality variables

might be attributed to the increase in water-specific conductivity.

In the areas where the rate of urbanization is high, the value of TDS is also recorded higher due to gradually decreased flow and deterioration of the aquatic systems by the accumulation of various inorganic as well as organic matters (Ternus et al., 2011). In the present study also, increased TDS was recorded from 146 ppm in 1960–1961 to 290 ppm in 2015–2019, which might be due to higher anthropogenic input associated with increased population and enhanced urbanization. in the region as discussed in specific conductivity.

The major cations responsible for the hardness of the water are calcium and magnesium and the associated anions are chlorides, carbonates, and bicarbonates (Kamboj & Kamboj, 2019). In the present observation, the hardness of the water has been recorded to

increase from 118 ppm in 1960–1961 to 148 ppm in 2001–2006; but got reduced to 138 ppm during 2015–2019. In many such studies, its effects have been described (Bellizzi et al., 1999; Comstock et al., 1979; Mitra et al., 2018). The consumption of hard water is harmful to human health as the consumption of 2 L of water per day having hardness 150–300 ppm can even cause several severe renal and cardiac diseases. The hardness of the water also affects various household activities such as washing clothes. In nature, hardness in the water is due to weathering of rocks and minerals containing magnesium and calcium. The presence of these minerals hinders the action of detergent (De Falco et al., 2018). The use of hard water can also cause severe diseases such as cancer, Alzheimer’s disease, cardiovascular disease, diabetes, and various reproductive disorders in humans as well as to various aquatic organisms (Sengupta, 2013). In the present study, the

Table 5 Correlation between WQI and different water quality variables

	DO	pH	FCO2	TALK	COND	TDS	HARD	CHLO	NITR	WQI
WQI	.175	.387	-.249	.440*	.582**	.557**	.528*	.564**	.375	1

*Correlation is significant at the 0.05 level (2-tailed)

**Correlation is significant at the 0.01 level (2-tailed)

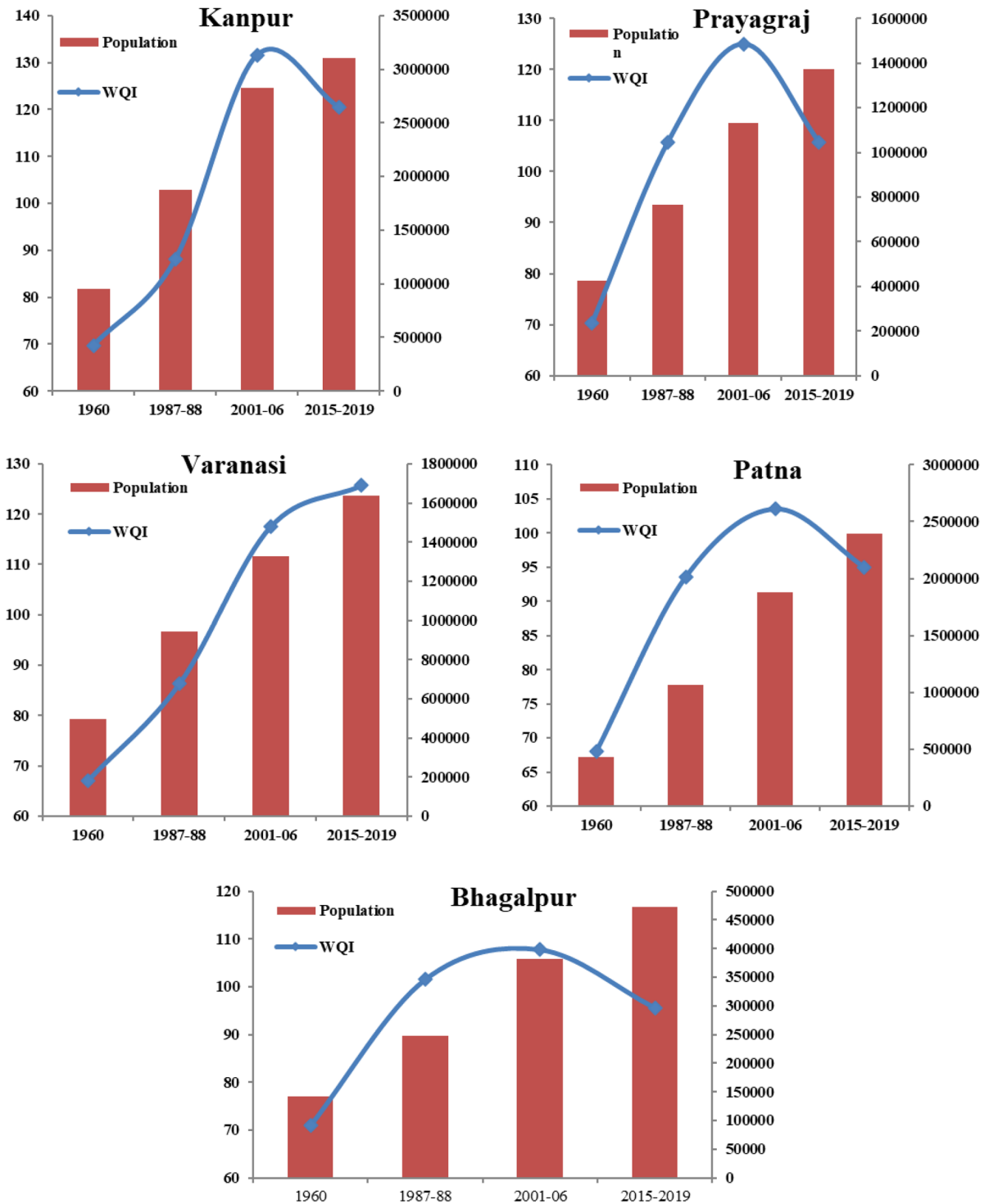
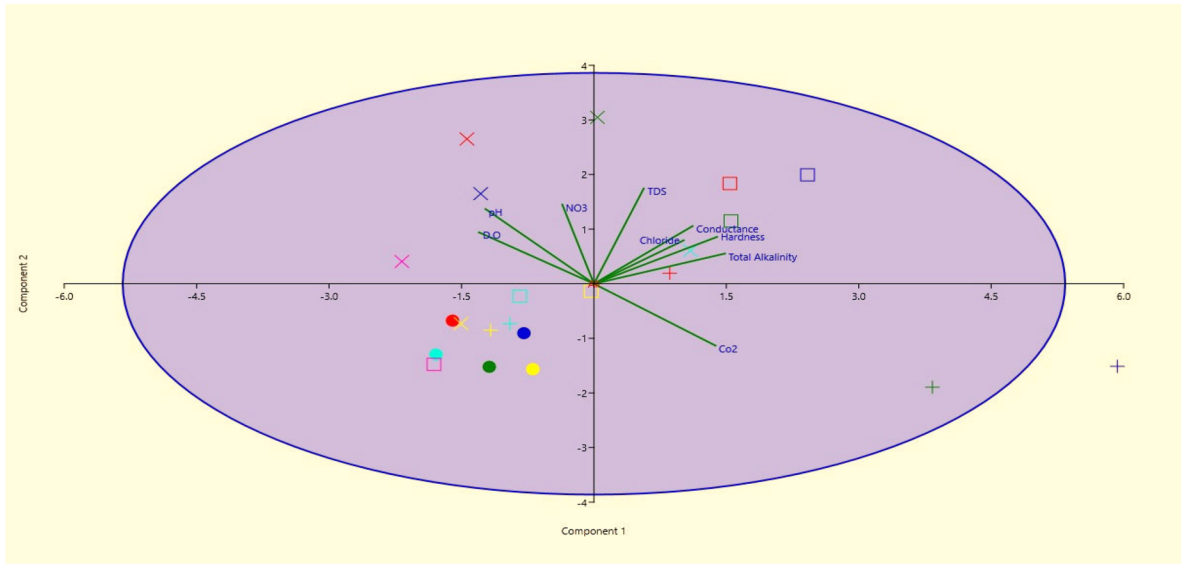


Fig. 19 Relationship between the increasing population at different studied sites and its impact on WQI



	KANPUR
	PRAYAGRAJ
	VARANASI
	PATNA
	BHAGALPUR
	FARRAKA

DOT	1960-61
PLUS	1987-88
SQUARE	2001-06
CROSS	2015-19

Fig. 20 Principal component analysis of different water quality parameters

hardness ranged from 118 to 148 ppm. Which is within the permissible range of drinking water sources.

Chloride is the essential electrolyte responsible for the maintenance of cellular homeostasis as well as an important pollution indicator (Hussain et al., 2021). The chloride content in the studied stretch of river Ganga raised from 23 ppm during 1960–1961 to 27 ppm during 2001–2006, but it got reduced to 12 ppm in the year 2015–2019. Similar, observation of the increased chloride values has also been reported from the other studies on river Ganga from the Kanpur stretch as reported by Shukla and Arya

(2018). However, in the entire period of 1960 to 2019, as per the BIS, the recorded range of chloride was much lower than the permissible limit of <250 ppm.

Nitrate is an important nutrient that enhances the productivity of the aquatic ecosystem (Matiatos et al., 2021), but its rise symbolizes eutrophication. The reason for the increase in nitrate concentration is may be reduced flow in the riverine system (Zhang et al., 2021). It is potentially harmful in the drinking water sources and long-term exposure can also be harmful to aquatic organisms (Vedachalam et al., 2019). In the present study, the low values of nitrates in the range

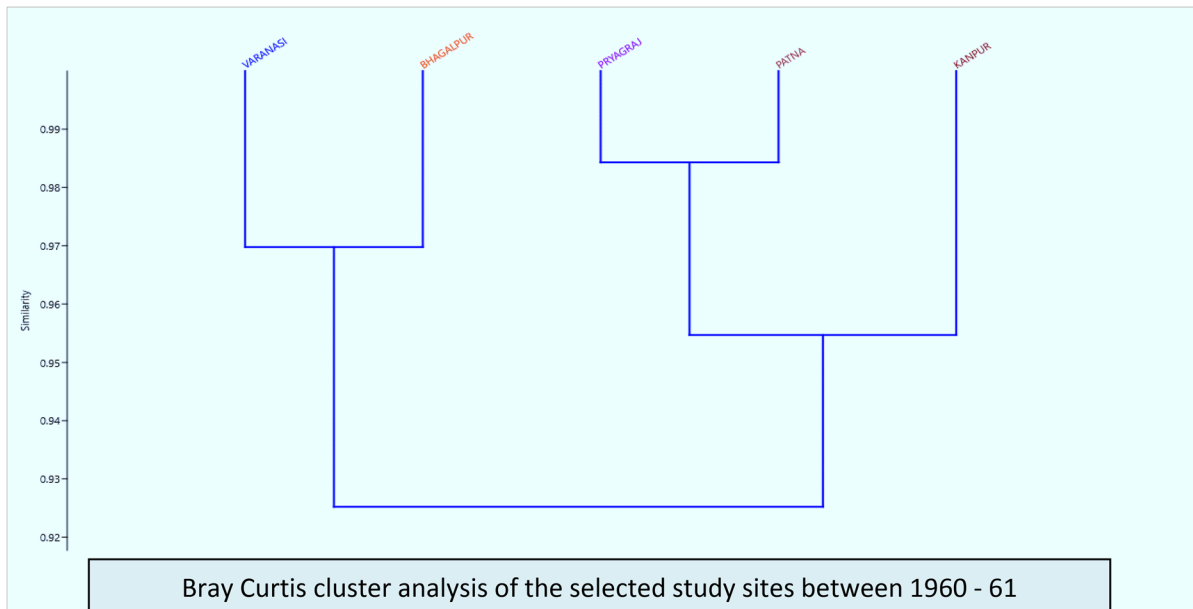
Table 6 Principal component analysis of different water quality parameters

	PC 1	PC 2	PC 3
D.O	-0.77	0.40	0.43
pH	-0.73	0.59	0.25
CO₂	0.81	-0.48	-0.25
Total alkalinity	0.88	0.24	0.37
Conductance	0.66	0.45	-0.05
TDS	0.33	0.75	-0.36
Hardness	0.82	0.37	0.19
Chloride	0.60	0.34	0.41
NO₃	-0.21	0.62	-0.71
Eigenvalue	4.17607	2.18634	1.27937
% Variance	46.401	24.293	14.215

of 0.14 to 0.70 ppm have been reported. The relatively higher values of nitrate during 2015–2019 (0.70 ppm) is a matter of concern and indicates the cause for local eutrophication of the riverine system especially during the reduced flow regime of non-monsoon months when a high amount of water is diverted at dams and barrages. The impact of urbanization in increasing the level of nitrate is also well known as in many of the studies; it has been reported that with the increase

in the population the rate of urbanization also gets increased. And increased urbanization results in the entry of more and more domestic sewages into the sewerage system. In the present study, also it was observed that with the increase in population the water quality has deteriorated as reflected in (Fig. 19). Similarly, with the increment in the population, the level of nitrate has also increased in the water. So, all the precautionary measures should be taken to restrict its further increase and gradually restrict it to its previous levels.

As per standard, permissible limits prescribed by various agencies majority of the parameters were within the permissible range. This may be due to the self-purification ability of the river (Dutta et al., 2020). It has also been observed nowadays during this COVID-19 lockdown. As during at many sites with the decreased human interventions, the river has restored cleaning status (Khan et al., 2021; Lokhandwala & Gautam, 2020). But in some of the cases, many of the alterations have been observed such as that of lower DO at Varanasi and Kanpur, the possible reasons may be excessive industrialization, the release of domestic wastes, and urbanization in the region (Vandana Singh et al., 2020; Tiwari & Manzoor, 1988). The study also showed that with the increasing industries such as

**Fig. 21** Bray Curtis cluster analysis of WQI generated from different sampling stations between 1960 and 1961

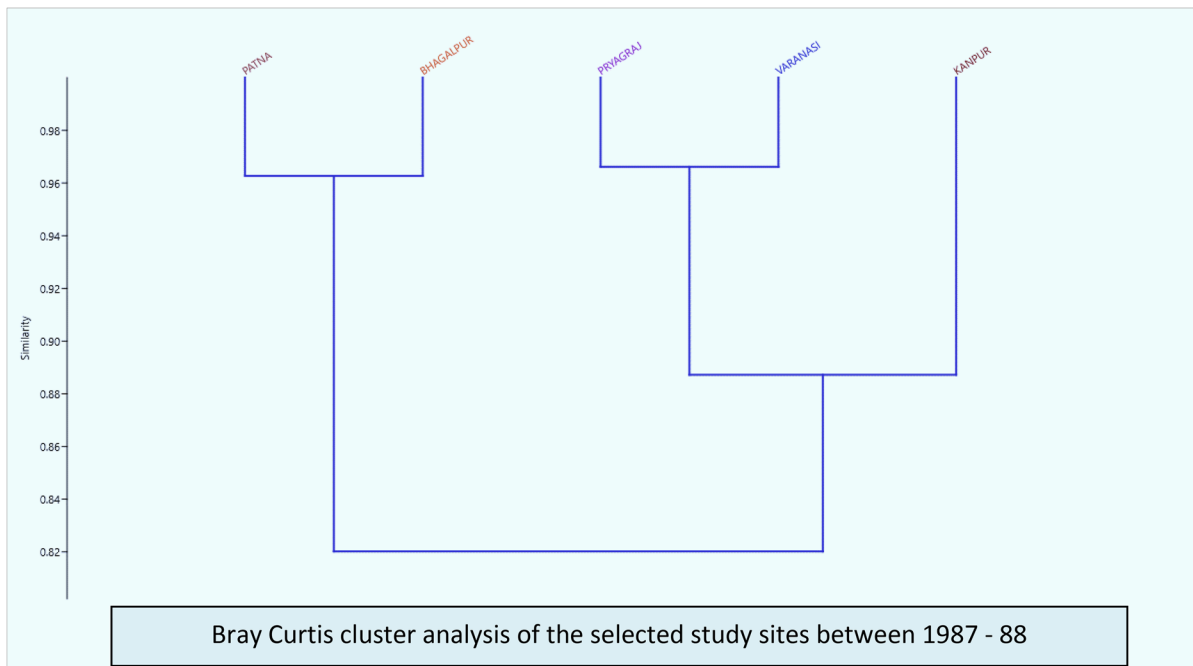


Fig. 22 Bray Curtis cluster analysis of WQI generated from different sampling stations between 1987 and 1988

leather and chemical factory in the region the pollution level has also been increased in the region. However, with the continuous effort of the Indian government which was initiated in 1985, the river has not further deteriorated and rather, comparatively improved as recorded during 2001–2006 and was at much better condition during 2015–2019.

Water quality index is an important tool to assess the water quality status of the riverine systems (Brown et al., 1970; Karunanidhi et al., 2021; Ustaoglu et al., 2020; Wu et al., 2018). The tool has been suitably utilized to assess the changing scenario of the Ganga River system as given in Table 4. The higher NSF-WQI values signify the deterioration in the water quality (Brown et al., 1970). The calculated WQI values exhibited a gradual increase in WQI from 1960–1961 to 2001–2006, which clearly expressed the gradual deterioration in the water quality of the studied river stretch. India had a population of 45 crores during 1960 and increased to 82, 107, and 131 crores during the years 1987, 2001, and 2015, respectively. Almost similar proportional population growth took place in the Ganga River basin. Thus, with the explosion in the population, various anthropogenic activities were intensified and industrial developments took place

resulting in the enhanced generation of domestic sewage and industrial effluents. The availability of sewage treatment plants concerning sewage generation is insufficient. Thus, a significant portion of untreated sewages is channelized directly into the river system. The channelization of sewage has resulted in the degradation of riverine water quality. Along with urbanization other significant issues such as global warming, climate change have also played an impactful role in it (Santy et al., 2020). The facts were similar to the earlier studies of Ona and Alaro river, Nigeria, and Pearl river China where the impact of global warming and change in climate have been observed (Osibanjo et al., 2011; Shen et al., 2017).

It was a good sign that the average WQI value has been reduced during 2015–2019. However, it is notable that during 2015–2019, all the sampling sites were having a very poor and unsuitable status of drinking water quality as per gradation provided by Brown et al. (1970). However, the relative reduction in the WQI values has been observed from 2001–2006 to 2015–2019 despite the rise in the population status of the country. The relative improvement in the WQI at all the sampling sites is may be due to the several conservation and restoration efforts taken by

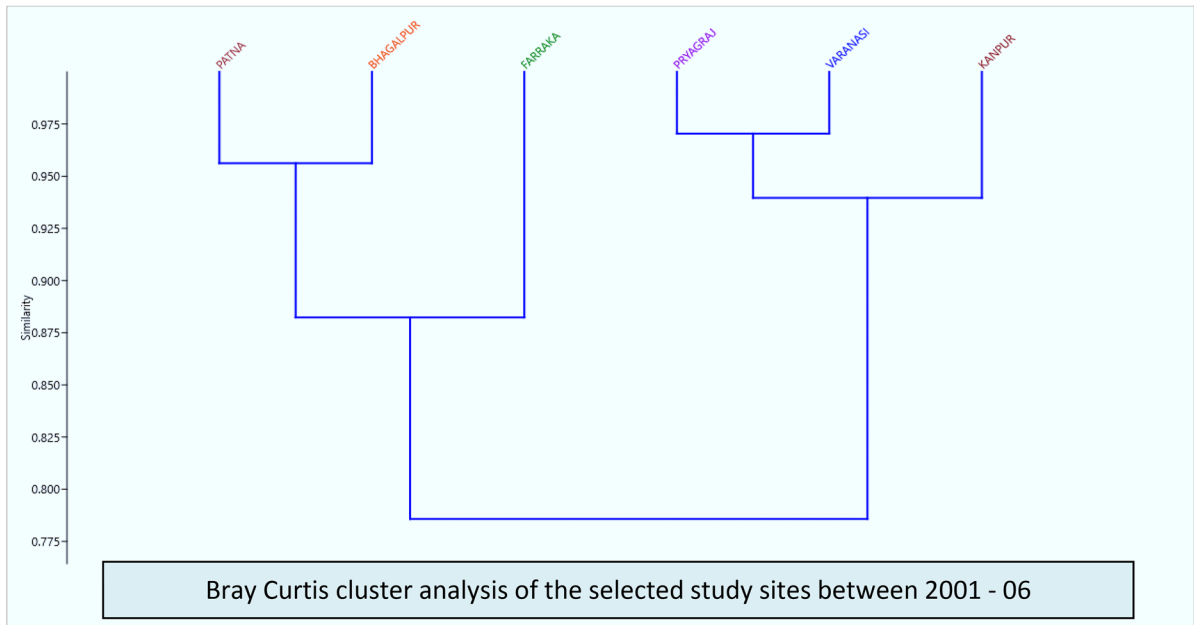


Fig. 23 Bray Curtis cluster analysis of WQI generated from different sampling stations between 2001 and 2006

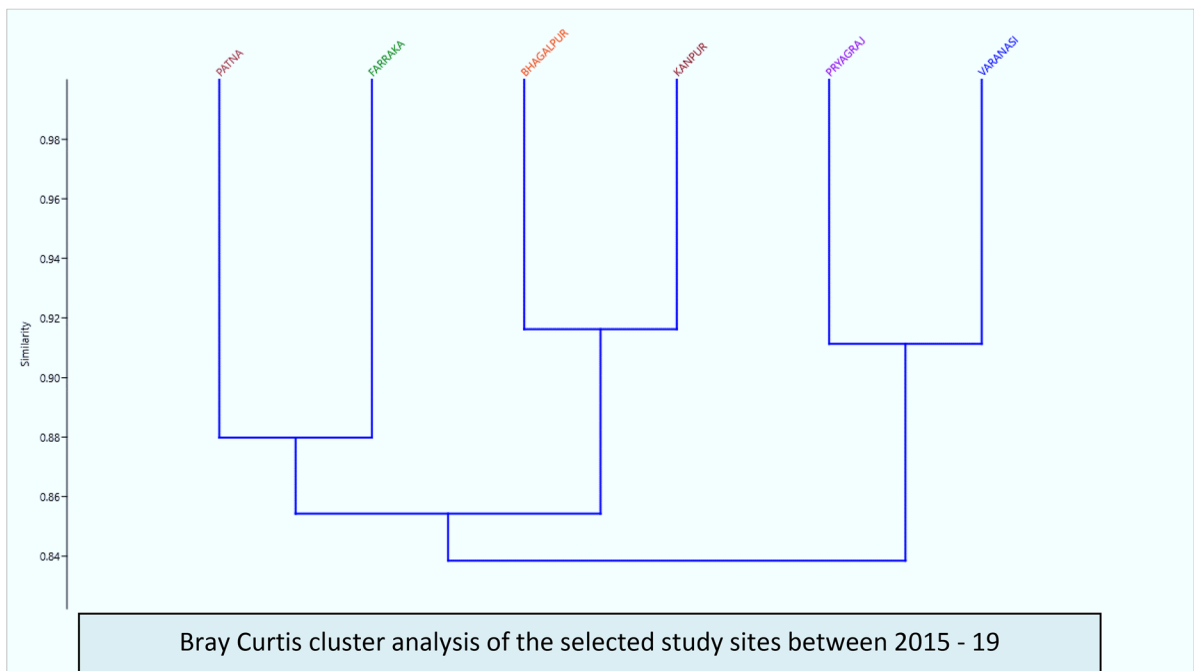


Fig. 24 Bray Curtis cluster analysis of WQI generated from different sampling stations between 2015 and 2019

Table 7 Results of two-way ANOVA for decadal and station significance at *p*-value (<0.05) of the statistically significant parameters is shown in bold font)

Parameter	Source of variation	Df	SS	MS	<i>F</i> value	<i>p</i> -value
DO	Decade	1	0.719	0.719	0.169	0.690
	Station	5	13.470	2.694	0.633	0.680
	Decade: station	5	2.184	0.437	0.103	0.989
	Residuals	10	42.588	4.259		
pH	Decade	1	0.293	0.293	3.474	0.092
	Station	5	0.249	0.050	0.591	0.708
	Decade: station	5	0.130	0.026	0.308	0.897
	Residuals	10	0.843	0.084		
Free CO ₂	Decade	1	12.882	12.882	1.120	0.315
	Station	5	15.440	3.088	0.268	0.920
	Decade: station	5	9.571	1.914	0.166	0.969
	Residuals	10	115.023	11.502		
Total alkalinity	Decade	1	176.855	176.855	0.206	0.660
	Station	5	3884.918	776.984	0.904	0.515
	Decade: station	5	889.303	177.861	0.207	0.952
	Residuals	10	8593.446	859.345		
Conductivity	Decade	1	50,330.084	50,330.084	7.033	0.024
	Station	5	110,894.194	22,178.839	3.099	0.060
	Decade: station	5	34,158.209	6831.642	0.955	0.488
	Residuals	10	71,557.876	7155.788		
TDS	Decade	1	49,965.768	49,965.768	19.570	0.001
	Station	5	43,829.735	8765.947	3.433	0.076
	Decade: station	5	18,872.507	3774.501	1.478	0.280
	Residuals	10	25,531.309	2553.131		
Hardness	Decade	1	1156.087	1156.087	2.331	0.158
	Station	5	4263.046	852.609	1.719	0.218
	Decade: station	5	683.491	136.698	0.276	0.916
	Residuals	10	4959.053	495.905		
Chloride	Decade	1	2.864	2.864	0.029	0.869
	Station	5	687.174	137.435	1.373	0.312
	Decade: station	5	159.334	31.867	0.318	0.891
	Residuals	10	1000.726	100.073		
Nitrate	Decade	1	0.682	0.682	10.018	0.010
	Station	5	0.231	0.046	0.678	0.650
	Decade: station	5	0.514	0.103	1.511	0.270
	Residuals	10	0.680	0.068		

the Government and various stakeholders of the Non-Government Societies in India. The implementation of various action plans like the Nirmal Dhara (aiming for pollution-free water) and Aviral Dhara (allowing the free flow of the river) (Srinivas et al., 2022; Tare et al., 2015) along with other river rejuvenation strategies are taken by various Non-Government and Government organizations had also made the significant improvement in the riverine water quality.

The impact of various anthropogenic factors on natural habitats is well documented. With the amplified impact of anthropogenic activities, various naturally occurring ecological niches have been destroyed (Lu et al., 2022). The deterioration of water quality and its impact on deterioration in the river Ganga ecology is noteworthy (Das et al., 2022). The reason for degradation in the riverine water quality is multiple environmental stressors (Rashid & Romshoo,

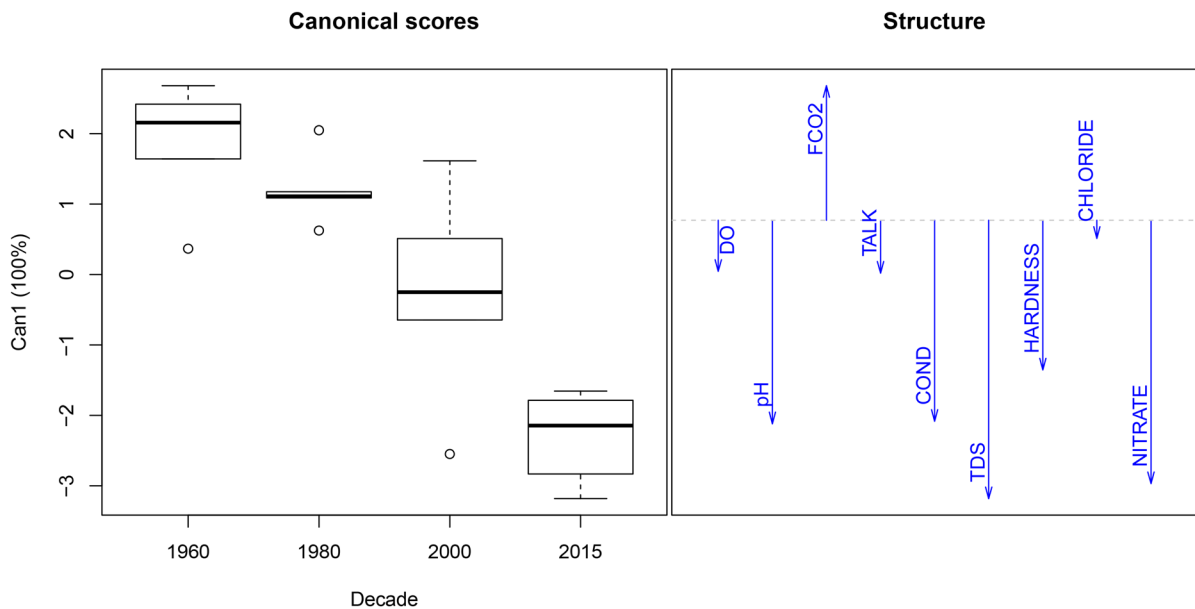


Fig. 25 Discriminant analysis of different studied water quality variables observed in different decades at different sampling sites

2013). There are multiple contributing factors, i.e., “stressors” responsible for it and the majority of them are; discharge of polluted domestic water, discharge of agricultural run-off, and industrial effluents. In the case of the river Ganga, also the main reasons which directly affect the water quality of the system are the same. Among the point source, the domestic and industrial discharge from the nearby households and industries has increased the pressure on the river. The major non-point source of pollution for the river is inorganic wastes from agricultural runoff containing harmful insecticides and pesticides which are

regularly being disposed of in the river. Carcasses and half-burned human flesh and animal bodies have also created a problem in it (Shukla & Tripathi, 2012; Tripathi & Tripathi, 2014), which has increased the organic pollution load in the river. As the population in the cities located on the bank of the river is increasing boisterously (Thakur et al., 2012), the increased population has resulted in a sewage discharge of more than 12,000 MLD from the class I and II cities (CPCB, 2013). But up to the year 2006, the available treatment capacity was only 4050 MLD. However, to cope with this huge difference in sewage

Table 8 Mean values of the observed water quality parameters

Year	1960–1961	1987–1988	2001–2006	2015–2019
Mean \pm SD				
Dissolved oxygen	7.42 \pm 0.66	5.4 \pm 3.12	7.48 \pm 0.34	7.23 \pm 0.69
pH	8.02 \pm 0.13	7.74 \pm 0.40	8.15 \pm 0.05	8.23 \pm 0.07
Free carbon dioxide	2.62 \pm 0.96	6.06 \pm 4.44	2.47 \pm 0.47	1.54 \pm 1.21
Total alkalinity	138.22 \pm 8.57	165.88 \pm 24.86	171.67 \pm 30.55	144 \pm 18.4
Conductivity	281.6 \pm 35.38	401.2 \pm 112.30	402.83 \pm 128.63	424.00 \pm 112
TDS	146 \pm 15.68	199.2 \pm 54.72	202.00 \pm 64.39	290.00 \pm 94.8
Hardness	118.4 \pm 7.40	144.00 \pm 24.70	148.00 \pm 27.50	138.30 \pm 19.60
Chloride	13.00 \pm 4.53	23.12 \pm 3.83	26.85 \pm 7.96	12.31 \pm 9.90
Nitrate	0.14 \pm 0.02	0.22 \pm 0.04	0.16 \pm 0.02	0.70 \pm 0.40

generation and its treatment procedure, the additional sewage treatment plants of 2172.68 MLD has been created, and additional STP of 1240 MLD has been started (NMCG, 2016) solid garbage wastes from regular households and industries, agricultural run-offs containing harmful insecticides and pesticides, and unburnt human fleshes buried in the river Ganga have directly or indirectly affected the ecotone among the riverine organisms (Joshi, 2022). The increased capacity of sewage treatment plants has however helped the river in attending the less polluted status as depicted in the WQI result from 2006 to 2019 where the average WQI from 2001 to 2006 has decreased from 113.40 to 106.48 in 2015–2019, depicting relatively less polluted status of the river among all the sampling stations.

The impact of industries on increasing the pollution in the river system is well known across the globe (Wu et al., 2019; Zheng et al., 2016). Similar to other rivers Ganga has also encountered a similar scenario (Arif et al. 2021). It has been estimated that industrial discharges are contributing about 20% of the sewage discharge in the river system (Roy & Shamim, 2020). The impact of industries can also be evaluated based on the recent studies made during the COVID-19 pandemic (Chakraborty et al., 2022; Lokhandwala & Gautam, 2020; Marwah & Agrawala, 2022; Singh & Mishra, 2021). The river Ganga is surrounded by many of the industries majority of them are leather industries, fertilizer industries, pharmaceutical industries, automobile industries, textile industries, paper industries, and color industry and many of the small-scale industries (CPCB, 2013). Among all the studied sites, the majority of the industries are located at Kanpur and among them, the majority are nearby located tanneries (Gowd et al., 2010). In Prayagraj, the glass factories, carpets, locomotive industries, fertilizer factories, and distilleries are the major factories located in the region (Gupta et al., 2009). Similar to Prayagraj Varanasi also has carpet industries, chemical factories, and many small-scale industries (Singh et al., 2018). At Patna, major industries are the surgical product manufacturing industry and small-scale industries (Rai et al., 2011). Bhagalpur and Farakka are having many small-scale industries. In the present study, also the higher WQI values at Kanpur, Prayagraj, and Varanasi significantly show the impact of the higher number of

industries in the region, which has deteriorated the water quality status of the river. Including the impact of industries at Varanasi, the impact of burning ghats, religious activities near the river banks, and responsible pollution load with the impact of amplified population load is visible in the study.

The principal component analysis is one of the most widely used multivariate statistical tools utilized for the analysis of water quality parameters worldwide and also in the river Ganga (Bagla et al., 2021; Dimri et al., 2021b; Tyagi et al., 2020; Verma & Kumar, 2020). So for the present study, the PCA analysis was carried out. In the analysis, it was observed that the 1st PC is having strong positive loading with FCO_2 , total alkalinity, conductance, hardness, and chloride, while strong negative loading was observed with dissolved oxygen and pH. The PC demonstrates the impact of pollution sources in the riverine system. The present observation of the pollution influencing parameters was similar to the studies made by other authors (Islam et al., 2021). In the upper stretch of the river also similar observations have been observed by (Dimri et al., 2021b). The 2nd PC shows a strong positive loading with pH, TDS, and nitrate, while no negative loading has been observed. The increment in the strong positive loading parameters is only seen in the case of eutrophication (Yao et al., 2022). The results of the 2nd PC were similar to that of Pearl river where an increased level of nitrate has resulted in the eutrophication of the river (Geeraert et al., 2021).

The cluster analysis from 1960 to 2006 showed that Kanpur was the only stretch that showed the least similarity with all the sampling sites. The difference was observed starting from 1960 to 2006. The most probable reason for the differentiation at Kanpur is maybe industrialization. As, after the 1960s the shifting of the industries has taken place from developed countries to developing countries like India (Gupta et al., 2017). For starting the factory, the best place was the river bank where the resources are very easily available. The data were unavailable for the Farraka sampling station for the period of 1960 to 1987. But based on the datasets of 2001–2006 and 2015–2019, it has been observed that Farakka showed the closest relationship with Bhagalpur and Patna, which was the closest sampling site. The observed similarity was due to a similar type of geomorphological environment, exhibited in both geographical locations.

The result of two-way ANOVA showed that only two of the parameters, i.e., TDS and conductivity have significantly varied among the stations. The different decades signifies the impact of increasing pollution load in the river. Both of the parameters are well-known physicochemical parameters used for the assessment of riverine pollution (Manna et al., 2013).

In the discriminant analysis, also it is observed that significant contribution was with TDS, nitrate, pH, conductivity, FCO₂, and hardness, while negligible contribution was observed with dissolved oxygen, total alkalinity, and chloride. The contribution of the parameters such as TDS, nitrate, conductivity, and free carbon dioxide shows the increasing pollution load in the river due to amplified pollution in the river (Pranavam et al., 2011).

Conclusion

The present study examined the multidecadal change in the water quality status of the river Ganga. It has been observed that increased population and anthropogenic activities have deteriorated the riverine water quality gradually during 1960–1961 to 2001–2006 (Fig. 26). But with the establishment and commissioning of the conservation and rejuvenation measures, taken by the Government and Non-government organizations, further deterioration in the water quality gradually stopped and then improved. The water quality has relatively improved as reflected by the decrease in WQI of 106.48 during 2015–2019. The major sampling stations where the impact of pollution is always seen are Kanpur, Prayagraj, and Varanasi.

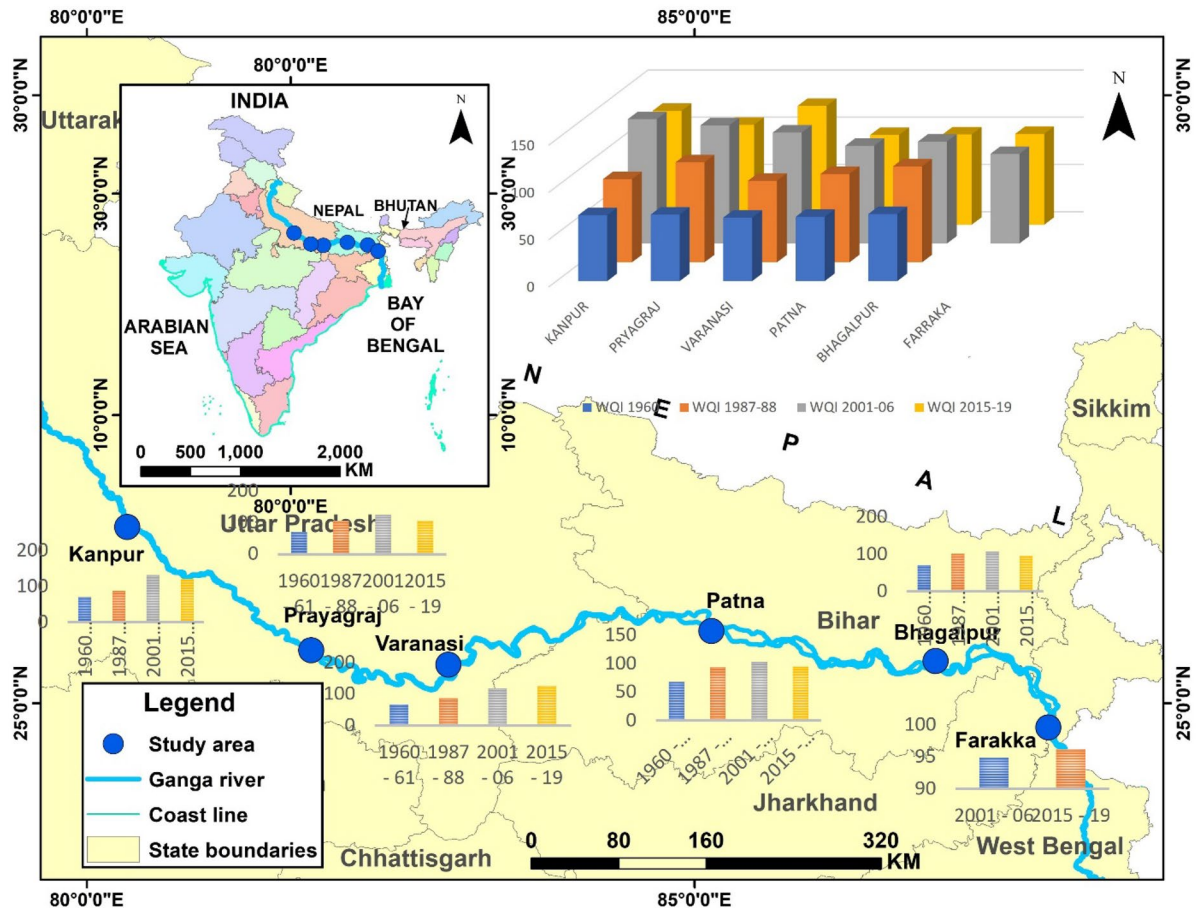


Fig. 26 Summarized WQI values at different sampling sites

Although the riverine water quality of Kanpur and Prayagraj has deteriorated from 1960 to 2006. Gradual improvement has also been observed in a few of the sampling stations. But at Varanasi, the quality of water has deteriorated over the decades. The impact of increasing population and its effect on increasing the pollution in the river is visible from the study. At the rest of the sampling stations, also the improvement in the water quality has been observed after 2006. The improved status of the WQI has been observed at Patna and Bhagalpur as well. The Farakka showed a negligible change from 2001–2006 to 2015–2019. The improvement in the water quality has become possible because of the increased management activities taken by the government by constructing more numbers of STPs. The involvement of public–private partnerships (PPP) has also positively influenced the scenario in the river. The water quality of the river Ganga is improving and gradually restoring to its relatively less polluted state. However, the adaptive measures planned for the conservation and restoration of the holy river Ganga should be strictly implemented to achieve the desired goal. Further to accelerate the rate of purification and reduce the pollution load in the river system, various mass public awareness programs should be carried out. In the process, digital and social media can also play a vital role. Since there are many social sites where Indians are the largest user. Strict measures like penalizing the polluters and imposing strict legal actions on the industries that are wrongdoers are also necessary. So, it is expected that the comprehensive effort of the local people, Government, Non-Government organizations, and social media may contribute significantly in achieving this herculean task along with the efforts taken by the Government.

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Data availability Experimental data will be provided by the corresponding authors on responsible request.

Declarations

Ethics approval All the above-mentioned work has been carried out as per approval of the Institute ethical committee, ICAR-CIFRI.

Conflict of interest The author declare no competing interests.

References

- Ansari, A., & Kumar, A. (2021). Water quality assessment of Ganga River along its course in India. *Innovative Infrastructure Solutions*, 7(1), 56. <https://doi.org/10.1007/s41062-021-00668-w>
- Ansari, A., & Kumar, A. (2022). Water quality assessment of Ganga River along its course in India. *Innovative Infrastructure Solutions*, 7(1), 1–9.
- APHA (2017). Standard methods for the examination of water and wastewater, 23rd edn. *American Public Health Association, American Water Works Association, Water Environment*.
- Arif, Z., Sethy, N. K., Mishra, P. K., & Verma, B. (2021). Grossly polluting industries and their effect on water resources in India. *Pollutants and Water Management: Resources, Strategies and Scarcity*, 47–65.
- Asadi Sharif, E., Yahyavi, B., Bayrami, A., Rahim Pouran, S., Atazadeh, E., Singh, R., & Abdul Raman, A. A. (2021). Physicochemical and biological status of Aghlagan river, Iran: Effects of seasonal changes and point source pollution. *Environmental Science and Pollution Research*, 28(12), 15339–15349. <https://doi.org/10.1007/s11356-020-11660-9>
- Azhar, S. C., Aris, A. Z., Yusoff, M. K., Ramli, M. F., & Juahir, H. (2015). Classification of river water quality using multivariate analysis. *Procedia Environmental Sciences*, 30, 79–84.
- Bagla, P., Kumar, K., Sharma, N., & Sharma, R. (2021). Multivariate analysis of water quality of Ganga River. *Journal of The Institution of Engineers (India): Series B*, 102(3), 539–549.
- Bellizzi, V., De Nicola, L., Minutolo, R., Russo, D., Cianciaruso, B., Andreucci, M., et al. (1999). Effects of water hardness on urinary risk factors for kidney stones in patients with idiopathic nephrolithiasis. *Nephron*, 81(SUPPL. 1), 66–70. <https://doi.org/10.1159/000046301>
- Bhargava, D. S. (1983). Use of water quality index for river classification and zoning of Ganga River. *Environmental Pollution Series B, Chemical and Physical*, 6(1), 51–67.
- Bilgin, A. (2018). Evaluation of surface water quality by using Canadian Council of Ministers of the Environment Water Quality Index (CCME WQI) method and discriminant analysis method: a case study Coruh River Basin. *Environmental Monitoring and Assessment*, 190(9). <https://doi.org/10.1007/s10661-018-6927-5>
- BIS. (2012). <http://cgwb.gov.in/Documents/WQ-standards.pdf>
- Brown, R. M., McClelland, N. I., Deininger, R. A., & Tozer, R. G. (1970). A water quality index-do we dare. *Water and sewage works*, 117(10).
- Carmichael, J. J. (1996). Impacts of climate change and seasonal variability on economic treatment costs: a case study of the Nitra River Basin, Slovakia. *International Journal of Water Resources Development*, 12(2), 209–228. <https://doi.org/10.1080/07900629650041966>

- Chakraborty, B., Bera, B., Adhikary, P. P., Bhattacharjee, S., Roy, S., Saha, S., et al. (2022). Effects of COVID-19 lockdown and unlock on the health of tropical large river with associated human health risk. *Environmental Science and Pollution Research*, 1–16.
- Chapman, D. V. (1996). *Water quality assessments: A guide to the use of biota, sediments and water in environmental monitoring*. CRC Press.
- Chauhan, A., & Singh, S. (2010). Evaluation of Ganga water for drinking purpose by water quality index at Rishikesh, Uttarakhand, India. *Report and Opinion*, 2(9), 53–61.
- Comstock, G. W., Cauthen, G. M., Helsing, K. J., & Goldberg, E. L. (1979). Stroke-associated deaths in Washington county, Maryland, with special reference to water hardness. *Stroke*, 10(2), 199–205. <https://doi.org/10.1161/01.STR.10.2.199>
- Cox, B. A., & Whitehead, P. G. (2009). Impacts of climate change scenarios on dissolved oxygen in the River Thames, UK. *Hydrology Research*, 40(2–3), 138–152.
- CPCB. (2013). <https://cpcb.nic.in/nwmp-data-2013/>
- Cude, C. G. (2001). Oregon water quality index a tool for evaluating water quality management effectiveness 1. *JAWRA Journal of the American Water Resources Association*, 37(1), 125–137.
- Das, M., Semy, K., & Kuotsu, K. (2022). Seasonal monitoring of algal diversity and spatiotemporal variation in water properties of Simsang river at South Garo Hills, Meghalaya, India. *Sustainable Water Resources Management*, 8(1), 1–9.
- De Falco, F., Gullo, M. P., Gentile, G., Di Pace, E., Cocca, M., Gelabert, L., et al. (2018). Evaluation of microplastic release caused by textile washing processes of synthetic fabrics. *Environmental Pollution*, 236, 916–925.
- Deshmukh, K. K., & Aher, S. P. (2016). Assessment of the impact of municipal solid waste on groundwater quality near the Sangamner City using GIS approach. *Water Resources Management*, 30(7), 2425–2443. <https://doi.org/10.1007/s11269-016-1299-5>
- Dimri, D., Daverey, A., Kumar, A., & Sharma, A. (2021a). Monitoring water quality of River Ganga using multivariate techniques and WQI (Water Quality Index) in Western Himalayan region of Uttarakhand, India. *Environmental Nanotechnology, Monitoring and Management*, 15, 100375. <https://doi.org/10.1016/j.enmm.2020.100375>
- Dimri, D., Daverey, A., Kumar, A., & Sharma, A. (2021b). Monitoring water quality of River Ganga using multivariate techniques and WQI (Water Quality Index) in Western Himalayan region of Uttarakhand, India. *Environmental Nanotechnology, Monitoring & Management*, 15, 100375.
- Dutta, V., Dubey, D., & Kumar, S. (2020). Cleaning the River Ganga: Impact of lockdown on water quality and future implications on river rejuvenation strategies. *Science of the Total Environment*, 743, 140756.
- Falkowski, P. G., Dubinsky, Z., & Wyman, K. (1985). Growth-irradiance relationships in phytoplankton 1. *Limnology and Oceanography*, 30(2), 311–321.
- Geeraert, N., Archana, A., Xu, M. N., Kao, S.-J., Baker, D. M., & Thibodeau, B. (2021). Investigating the link between Pearl River-induced eutrophication and hypoxia in Hong Kong shallow coastal waters. *Science of the Total Environment*, 772, 145007.
- Goel, P. K. (2006). *Water pollution: causes, effects and control*. New Age International.
- Gowd, S. S., Reddy, M. R., & Govil, P. K. (2010). Assessment of heavy metal contamination in soils at Jajmau (Kanpur) and Unnao industrial areas of the Ganga Plain, Uttar Pradesh, India. *Journal of Hazardous Materials*, 174(1–3), 113–121.
- Gupta, A., Rai, D. K., Pandey, R. S., & Sharma, B. (2009). Analysis of some heavy metals in the riverine water, sediments and fish from river Ganges at Allahabad. *Environmental Monitoring and Assessment*, 157(1), 449–458.
- Gupta, N., Pandey, P., & Hussain, J. (2017). Effect of physico-chemical and biological parameters on the quality of river water of Narmada, Madhya Pradesh, India. *Water Science*, 31(1), 11–23. <https://doi.org/10.1016/j.wsj.2017.03.002>
- Gyimah, R. A. A., Gyamfi, C., Anornu, G. K., Karikari, A. Y., & Tsyawo, F. W. (2021). Multivariate statistical analysis of water quality of the Densu River, Ghana. *International Journal of River Basin Management*, 19(2), 189–199. <https://doi.org/10.1080/15715124.2020.1803337>
- Hare, A., Evans, W., Pocock, K., Weekes, C., & Gimenez, I. (2020). Contrasting marine carbonate systems in two fjords in British Columbia, Canada: Seawater buffering capacity and the response to anthropogenic CO₂ invasion. *PLoS ONE*. <https://doi.org/10.1371/journal.pone.0238432>
- Horton, R. K. (1965). An index number system for rating water quality. *Journal of Water Pollution Control Federation*, 37(3), 300–306.
- Hussain, M., Jamir, L., & Singh, M. R. (2021). Assessment of physico-chemical parameters and trace heavy metal elements from different sources of water in and around institutional campus of Lumami, Nagaland University, India. *Applied Water Science*, 11(4), 1–21. <https://doi.org/10.1007/s13201-021-01405-5>
- Iqbal, K., Ahmad, S., & Dutta, V. (2019). Pollution mapping in the urban segment of a tropical river: Is water quality index (WQI) enough for a nutrient-polluted river? *Applied Water Science*, 9(8), 1–16. <https://doi.org/10.1007/s13201-019-1083-9>
- Islam, M. M., Bhuiyan, M. H. S. S., Islam, R., Shoeb, M., Mamun, M. I. R., & Rahman, M. H. (2021). Physico-chemical properties and metal ions in water and sediment of the Dhaleshwari River. *The Dhaka University Journal of Science*, 69(1), 37–42.
- Johnstone, C., Bedaso, Z. K., & Ekberg, M. (2022). Characterizing surface water and groundwater interaction for sustainable water resources management in southwestern Ohio. *Sustainable Water Resources Management*, 8(1), 1–16.
- Joshi, B. D. (2022). Ambient ecological conditions of the Gangetic dolphin-Platanista gangetica gangetica of river Ganga, between Varanasi to Farakka. In *Advances in Animal Experimentation and Modeling* (pp. 253–266). Elsevier.
- Jung, K. Y., Lee, K.-L., Im, T. H., Lee, I. J., Kim, S., Han, K.-Y., & Ahn, J. M. (2016). Evaluation of water quality for the Nakdong River watershed using multivariate analysis. *Environmental Technology & Innovation*, 5, 67–82.

Kamboj, N., & Kamboj, V. (2019). Water quality assessment using overall index of pollution in riverbed-mining area of Ganga-River Haridwar, India. *Water Science*, 33(1), 65–74. <https://doi.org/10.1080/11104929.2019.1626631>

Kannel, P. R., Lee, S., Lee, Y.-S., Kanel, S. R., & Khan, S. P. (2007). Application of water quality indices and dissolved oxygen as indicators for river water classification and urban impact assessment. *Environmental Monitoring and Assessment*, 132(1), 93–110.

Karunanidhi, D., Aravinthasamy, P., Subramani, T., & Muthusankar, G. (2021). Revealing drinking water quality issues and possible health risks based on water quality index (WQI) method in the Shanmuganadhi River basin of South India. *Environmental Geochemistry and Health*, 43(2), 931–948.

Khan, R., Saxena, A., & Shukla, S. (2021). Assessment of the impact of COVID-19 lockdown on the heavy metal pollution in the River Gomti, Lucknow city, Uttar Pradesh, India. *Environmental Quality Management*.

Kumar, A., Matta, G., & Bhatnagar, S. (2021). A coherent approach of Water Quality Indices and Multivariate Statistical Models to estimate the water quality and pollution source apportionment of River Ganga System in Himalayan region, Uttarakhand, India. *Environmental Science and Pollution Research*, 28(31), 42837–42852. <https://doi.org/10.1007/s11356-021-13711-1>

Kumar, M., & Puri, A. (2012). A review of permissible limits of drinking water. *Indian Journal of Occupational and Environmental Medicine*, 16(1), 40–44. <https://doi.org/10.4103/0019-5278.99696>

Liyanage, C. P., & Yamada, K. (2017). Impact of population growth on the water quality of natural water bodies. *Sustainability*, 9(8), 1405.

Lokhandwala, S., & Gautam, P. (2020). Indirect impact of COVID-19 on environment: A brief study in Indian context. *Environmental Research*, 188, 109807.

Lu, L., Tang, Q., Li, H., & Li, Z. (2022). Damming river shapes distinct patterns and processes of planktonic bacterial and microeukaryotic communities. *Environmental Microbiology*.

Lumb, A., Sharma, T. C., & Bibeault, J.-F. (2011). A review of genesis and evolution of water quality index (WQI) and some future directions. *Water Quality, Exposure and Health*, 3(1), 11–24. <https://doi.org/10.1007/s12403-011-0040-0>

Manna, R. K., Satpathy, B. B., Roshith, C. M., Naskar, M., Bhaumik, U., & Sharma, A. P. (2013). Spatio-temporal changes of hydro-chemical parameters in the estuarine part of the river Ganges under altered hydrological regime and its impact on biotic communities. *Aquatic Ecosystem Health & Management*, 16(4), 433–444.

Marwah, M., & Agrawala, P. K. (2022). COVID-19 lockdown and environmental pollution: An Indian multi-state investigation. *Environmental Monitoring and Assessment*, 194(2), 1–15.

Matiatos, I., Wassenaar, L. I., Monteiro, L. R., Venkiteswaran, J. J., Gooddy, D. C., Boeckx, P., et al. (2021). Global patterns of nitrate isotope composition in rivers and adjacent aquifers reveal reactive nitrogen cascading. *Communications Earth & Environment*, 2(1), 1–10.

Matta, G. (2014). A study on physico-chemical Characteristics to assess the pollution status of river Ganga in Uttarakhand. *Journal of Chemical and Pharmaceutical Sciences*, 7(3), 210–217.

Mazinder Baruah, P., & Singh, G. (2022). Assessment of potability of minewater pumped out from Jharia Coalfield, India: An integrated approach using integrated water quality index, heavy metal pollution index, and multivariate statistics. *Environmental Science and Pollution Research*, (0123456789). <https://doi.org/10.1007/s11356-021-17918-0>

Mitra, S., Ghosh, S., Satpathy, K. K., Bhattacharya, B. D., Sarkar, S. K., Mishra, P., & Raja, P. (2018). Water quality assessment of the ecologically stressed Hooghly River Estuary, India: A multivariate approach. *Marine Pollution Bulletin*, 126, 592–599.

Mohanty, T. R., Tiwari, N. K., Kumari, S., Ray, A., Manna, R. K., Bayen, S., et al. (2022). Variation of *Aulacoseira granulata* as an eco-pollution indicator in subtropical large river Ganga in India: A multivariate analytical approach. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-021-18096-9>

Mustapha, A., Aris, A. Z., Juahir, H., Ramli, M. F., & Kura, N. U. (2013). River water quality assessment using environmental techniques: Case study of Jakara River Basin. *Environmental Science and Pollution Research*, 20(8), 5630–5644. <https://doi.org/10.1007/s11356-013-1542-z>

Njuguna, S. M., Onyango, J. A., Githaiga, K. B., Gituru, R. W., & Yan, X. (2020). Application of multivariate statistical analysis and water quality index in health risk assessment by domestic use of river water. Case study of Tana River in Kenya. *Process Safety and Environmental Protection*, 133, 149–158.

NMCG. (2016). National mission for clean Ganga. *Ministry of Water Resources, River Development & Ganga Rejuvenation*, 21. https://nmcg.nic.in/about_nmcg.aspx. Accessed 24 March 2021.

Noori, R., Berndtsson, R., Hosseinzadeh, M., Adamowski, J. F., & Abyaneh, M. R. (2019). A critical review on the application of the National Sanitation Foundation Water Quality Index. *Environmental Pollution*, 244, 575–587.

Olin Neal, C. (2001). Alkalinity measurements within natural waters: Towards a standardised approach. *Science of the Total Environment*, 265(1–3), 99–113.

Osibanjo, O., Daso, A. P., & Gbadebo, A. M. (2011). The impact of industries on surface water quality of River Ona and River Alaro in Oluyole Industrial Estate, Ibadan. *Nigeria. African Journal of Biotechnology*, 10(4), 696–702.

Parida, P. K., Kayal, T., Das, B. K., Sarkar, U. K., Koushlesh, S. K., & Behera, B. K. (2022). Spatio-temporal changes in ecology and fisheries in a tropical large Indian reservoir: Insights from a long-term data series for sustainable development. *Environmental Science and Pollution Research*, 1–13.

Paul, V., Sankar, M. S., Vattikuti, S., Dash, P., & Arslan, Z. (2021). Pollution assessment and land use land cover influence on trace metal distribution in sediments from five aquatic systems in southern USA. *Chemosphere*, 263, 128243. <https://doi.org/10.1016/j.chemosphere.2020.128243>

- Pranavam, T. S. D., Rao, T. V., Punithavathi, L., Karunanithi, S., & Bhaskaran, A. (2011). Groundwater pollution in the Palar Riverbed near Vellore, Tamil Nadu, India. *Indian Journal of Science and Technology*, 4(1), 19–21.
- Rai, A. K., Paul, B., Mudra, L., & Kishor, N. (2011). Studies of selected water quality parameters of river Ganges at Patna, Bihar. *Journal of Advanced Laboratory Research in Biology*, 2(4), 136–140.
- Rashid, I., & Romshoo, S. A. (2013). Impact of anthropogenic activities on water quality of Lidder River in Kashmir Himalayas. *Environmental Monitoring and Assessment*, 185(6), 4705–4719. <https://doi.org/10.1007/s10661-012-2898-0>
- Roy, M., & Shamim, F. (2020). Research on the impact of industrial pollution on River Ganga: A Review. *International Journal of Prevention and Control of Industrial Pollution*, 6(1), 43–51.
- Roy, R., & Majumder, M. (2022). Assessment of water quality trends in Deepor Beel, Assam, India. *Environment, Development and Sustainability*. <https://doi.org/10.1007/s10668-021-02033-4>
- Samanta, S. (2013). Metal and pesticide pollution scenario in Ganga River system. *Aquatic Ecosystem Health & Management*, 16(4), 454–464.
- Santy, S., Mujumdar, P., & Bala, G. (2020). Potential impacts of climate and land use change on the water quality of Ganga River around the industrialized Kanpur Region. *Scientific Reports*, 10(1), 9107. <https://doi.org/10.1038/s41598-020-66171-x>
- Sengupta, P. (2013). *Potential health impacts of hard water*. *International Journal of Preventive Medicine* (vol. 4). www.ijpm.ir. Accessed 24 March 2021.
- Sharma, S., Dixit, S., Jain, P., Shah, K. W., & Vishwakarma, R. (2008). Statistical evaluation of hydrobiological parameters of Narmada River water at Hoshangabad City, India. *Environmental Monitoring and Assessment*, 143(1), 195–202.
- Shen, J., Wei, Y. D., & Yang, Z. (2017). The impact of environmental regulations on the location of pollution-intensive industries in China. *Journal of Cleaner Production*, 148, 785–794.
- Shukla, M., & Arya, S. (2018). Determination of chloride ion(Cl⁻) CONCENTRATION IN Ganga River water by mohr method at Kanpur, India. *Green Chemistry & Technology Letters*, 4(1), 06–08. <https://doi.org/10.18510/gctl.2018.412>
- Shukla, P., & Tripathi, B. D. (2012). 4. River Ganga at Varanasi the polluted purifier by Priyadarshini Shukla and BD Tripathi. *Life Sciences Leaflets*, 28, 24-to.
- Singh, A. N., Shrivastava, R., Mohan, D., & Kumar, P. (2018). Assessment of spatial and temporal variations in water quality dynamics of river Ganga in Varanasi. *Pollution*, 4(2), 239–250.
- Singh, A. P., Dhadse, K., & Ahalawat, J. (2019). Managing water quality of a river using an integrated geographically weighted regression technique with fuzzy decision-making model. *Environmental Monitoring and Assessment*, 191(6). <https://doi.org/10.1007/s10661-019-7487-z>
- Singh, V., Nagpoore, N. K., & Jaichand, & Lehri, A. (2020). Monitoring and assessment of pollution load in surface water of River Ganga around Kanpur, India: A study for suitability of this water for different uses. *Environmental Technology and Innovation*, 18, 100676. <https://doi.org/10.1016/j.eti.2020.100676>
- Singh, V., & Mishra, V. (2021). Environmental impacts of coronavirus disease 2019 (COVID-19). *Bioresource Technology Reports*, 15, 100744.
- Sinha, R. K. (2015). Ecology of the River Ganga-Issues and challenges. *Society and Technology: Impact, Issues and Challenges*. Janaki Prakashan, St. Xavier College of Management & Technology, and Xavier Institute of Social Research, Patna, Bihar, India, 292–317.
- Srinivas, R., Das, B., & Singhal, A. (2022). Integrated watershed modeling using interval valued fuzzy computations to enhance watershed restoration and protection at field-scale. *Stochastic Environmental Research and Risk Assessment*, 1–17.
- Tappin, A. D., Navarro-Rodriguez, A., Comber, S. D. W., & Worsfold, P. J. (2018). The role of alkalinity in setting water quality metrics: Phosphorus standards in United Kingdom rivers. *Environmental Science: Processes & Impacts*, 20(10), 1361–1372.
- Tare, V., Roy, G., & Bose, P. (2013). *Ganga River Basin environment management plan: interim report*, (August), 17–114.
- Tare, V., Roy, G., & Bose, P. (2015). *Ganga river basin management plan-Extended summary*, (January), 30.
- Ternus, R. Z., de Souza-Franco, G. M., Anselmini, M. E. K., Mocellin, D. J. C., & Dal Magro, J. (2011). Influence of urbanisation on water quality in the basin of the upper Uruguay River in western Santa Catarina, Brazil. *Acta Limnologica Brasiliensia*, 23, 189–199.
- Thakur, P. K., Laha, C., & Aggarwal, S. P. (2012). River bank erosion hazard study of river Ganga, upstream of Farakka barrage using remote sensing and GIS. *Natural Hazards*, 61(3), 967–987.
- Tiwari, J. N., & Manzoor, A. (1988). *Water quality index for Indian rivers* (pp. 271–286). Ecology and pollution of Indian rivers. Aashish Publishing House.
- Tripathi, B. D., & Tripathi, S. (2014). Issues and challenges of river Ganga. In *Our National River Ganga* (pp. 211–221). Springer.
- Trivedi, R. C. (2010). Water quality of the Ganga River—An overview. *Aquatic Ecosystem Health & Management*, 13(4), 347–351.
- Tyagi, S., Dubey, R. C., Bhutiani, R., & Ahamad, F. (2020). Multivariate statistical analysis of river Ganga water at Rishikesh and Haridwar, India. *Analytical Chemistry Letters*, 10(2), 195–213.
- Ustaoglu, F., Tepe, Y., & Taş, B. (2020). Assessment of stream quality and health risk in a subtropical Turkey river system: A combined approach using statistical analysis and water quality index. *Ecological Indicators*, 113, 105815.
- Vass, K. K., Mondal, S. K., Samanta, S., Suresh, V. R., & Katiha, P. K. (2010). The environment and fishery status of the River Ganges. *Aquatic Ecosystem Health & Management*, 13(4), 385–394.
- Vass, K. K., Tyagi, R. K., Pathak, V., Singh, H. P., & Seth, R. N. (2008). The status of the river Ganges in the middle stretch. *CIFRI Bull*, 154, 25.

- Vedachalam, S., Mandelia, A. J., & Heath, E. A. (2019). The impact of source water quality on the cost of nitrate treatment. *AWWA Water Science*, *1*(1), e1011.
- Verma, M., & Kumar, R. (2020). Impact of efforts on Ganga restoration and conservation. *Environment, Development and Sustainability in India: Perspectives, Issues and Alternatives*, 115–147.
- Wang, Q., Li, Z., Xu, Y., Li, R., & Zhang, M. (2022). Analysis of spatio-temporal variations of river water quality and construction of a novel cost-effective assessment model: A case study in Hong Kong. *Environmental Science and Pollution Research*, (0123456789). <https://doi.org/10.1007/s11356-021-17885-6>
- Wu, J., Wei, Y. D., Chen, W., & Yuan, F. (2019). Environmental regulations and redistribution of polluting industries in transitional China: Understanding regional and industrial differences. *Journal of Cleaner Production*, *206*, 142–155.
- Wu, Z., Wang, X., Chen, Y., Cai, Y., & Deng, J. (2018). Assessing river water quality using water quality index in Lake Taihu Basin, China. *Science of the Total Environment*, *612*, 914–922.
- Xiao, K., Tamborski, J., Wang, X., Feng, X., Wang, S., Wang, Q., et al. (2022). A coupling methodology of the analytic hierarchy process and entropy weight theory for assessing coastal water quality. *Environmental Science and Pollution Research*, (Moore 2010). <https://doi.org/10.1007/s11356-021-17247-2>
- Yao, H., Wang, J., Han, Y., Jiang, X., & Chen, J. (2022). Decadal acidification in a subtropical coastal area under chronic eutrophication. *Environmental Pollution (Barking, Essex: 1987)*, *293*, 118487. <https://doi.org/10.1016/j.envpol.2021.118487>
- Zhang, M., Huang, J.-C., Sun, S., Rehman, M. M. U., He, S., & Zhou, W. (2021). Dissimilatory nitrate reduction processes and corresponding nitrogen loss in tidal flow constructed wetlands. *Journal of Cleaner Production*, *295*, 126429.
- Zheng, J., Jiang, P., Qiao, W., Zhu, Y., & Kennedy, E. (2016). Analysis of air pollution reduction and climate change mitigation in the industry sector of Yangtze River Delta in China. *Journal of Cleaner Production*, *114*, 314–322.

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